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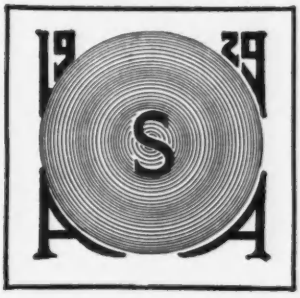

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Frequency Distribution of Normal Modes

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(Received April 10, 1941)

The formula obtained by Maa for the frequency distribution of the normal modes for a rectangular enclosure has been verified by a more direct computation and extended to apply to a cylinder, a sphere, and to a number of derived shapes. In all cases it is found that the number of normal modes with frequencies less than ν is given by $4\pi V\nu^3/3c^3+\pi A\nu^2/4c^2+\cdots$, where V is the volume and A the surface area of the enclosure. The application of this result is illustrated by a calculation of resonance response and rate of decay of sound in a cylinder.

IT has been pointed out by several authors* that the failure of Sabine's law for small rooms is due in large part to the use of a frequency distribution function which is accurate only for high frequencies. Strutt[1] has shown that the theoretical basis of Sabine's law lies in the work of Courant[2] and Weyl,[3] who prove that if $N(\nu)$ is the number of solutions with frequencies less than ν of the wave equation

$$\nabla^2\psi+4\pi^2\nu^2\psi/c^2=0 \qquad (1)$$

with $2\psi/2n=0$ (or $\psi=0$) on the boundary, then

$$\lim_{\nu\to\infty}\frac{N(\nu)c^3}{V\nu^3}=\frac{4\pi}{3}$$

for an enclosure of volume V and arbitrary shape That is, the asymptotic value of the frequency distribution of normal modes is, for high frequencies, independent of the shape of the enclosure. Since this is only an asymptotic approximation to $N(\nu)$, the error itself may be infinite. A better approximation will be obtained if it is assumed that $N(\nu)$ may be expanded as a power series in ν, the coefficient of the second term, from dimensional arguments, being linear in the surface area A.

$$N(\nu)=4\pi V\nu^3/3c^3+(\text{constant})\,A\nu^2/c+\cdots. \qquad (2)$$

Strictly, Courant's theory can only show that the second term on the right in (2) is less than a constant times $\nu^2\log\nu$. However, as will be shown below, the expansion is valid for a number of simple shapes at least.

The problem of reverberation time in rectangular rooms has been discussed rather com-

* See, for example, references 4, 5, 6.
[1] M. J. O. Strutt, Phil. Mag. **8**, 236 (1929).
[2] R. Courant and D. Hilbert, *Methoden der Mathematische Physik* (Julius Springer, Berlin, 1924), p. 355.
[3] H. Weyl, Math. Ann. **71**, 441 (1912).

pletely by Hunt, Beranek, and Maa,[4] taking account of the correction to the distribution formula. A similar solution should be possible in all cases in which the wave equation is easily soluble, i.e., the sphere, cylinder, etc. While these shapes are of little practical importance it will be of interest to study them in order to note the similarities with the solution for the rectangle, and in particular to see what happens to the symmetry factors σ which appear in the rectangular case.

The first four sections will be concerned with the determination of the form of the distribution function, the later sections with the application to sound absorption.

I. Rectangular Rooms

The solution of the wave equation is

$$\psi=\cos(n_x\pi x/L_x)\cos(n_y\pi y/L_y)\cos(n_z\pi z/L_z), \quad (3)$$

$$\nu=\tfrac{1}{2}c[(n_x/L_x)^2+(n_y/L_y)^2+(n_z/L_z)^2]^{\frac{1}{2}}. \quad (4)$$

$N(\nu)$ is usually represented as the number of points in the positive octant of an ellipse in frequency space.[4] By counting these points Maa[5] obtains

$$N(\nu)=\frac{4\pi V\nu^3}{3c^3}+\frac{\pi A\nu^2}{4c^2}+\frac{L\nu}{2c} \quad (5)$$

$$L=L_x+L_y+L_z, \quad A=2(L_xL_y+L_yL_z+L_zL_x),$$

whereas Bolt,[6] with a different method of counting, finds

$$N(\nu)=\frac{4\pi V\nu^3}{3c^3}\left[\frac{2V\nu+cR^{\frac{1}{2}}}{2V\nu+\frac{1}{2}cR^{\frac{1}{2}}}\right]^3,$$

$$R=L_x^2+L_y^2+L_z^2.$$

In view of this discrepancy, it might be well to determine $N(\nu)$ by a more direct method. The number of solutions of

$$\nu\geqq\tfrac{1}{2}c[(n_x/L_x)^2+(n_y/L_y)^2+(n_z/L_z)^2]^{\frac{1}{2}}$$

$$n_x, n_y, n_z=0, 1, 2, 3, \cdots$$

for fixed n_x and n_y is

$$[(2\nu/c)^2-(n_x/L_x)^2-(n_y/L_y)^2]^{\frac{1}{2}}L_z+1.$$

Summing over n_y from 0 to

$$n_y'=L_y[(2\nu/c)^2-(n_x/L_y)^2]^{\frac{1}{2}}, \quad (6)$$

and over n_x from 0 to $2\nu L_x/c$ gives

$$N(\nu)=\sum_{n_x=0}^{2\nu L_x/c}\left\{\sum_{n_y=0}^{n_y'}\left[1+\frac{L_z}{L_y}(n_y'^2-n_y^2)^{\frac{1}{2}}\right]\right\}-1. \quad (7)$$

The sum may be evaluated by expanding $(n_y'^2-n_y^2)^{\frac{1}{2}}$ in a power series, using Euler's summation formula on the powers of n_y, and then repeating the process on the expansion of n_y' in powers of n_x.[7] Reduction of the resulting infinite series yields Eq. (5) for $N(\nu)$. The same result is obtained by Husimi,[8] who uses a method involving inversion of the theta-function.

Note that Eq. (6) will not in general be integral valued, but that n_y' in (7) is taken to be an integer. The error due to this approximation affects only the third term of Eq. (5), and corresponds to neglecting the fluctuations in the number of points within the frequency ellipse. Since $N(\nu)$ is to be differentiated for the final result, fluctuations of the order of magnitude of the term in ν/c are unimportant. Similar approximations will be made in all the examples below.

II. Cylinder

The wave functions for a cylinder of radius a and altitude L are

$$\psi=\begin{pmatrix}\sin\\ \cos\end{pmatrix}m\phi\cos\frac{n\pi z}{L}J_m\left(\rho_{im}\frac{r}{a}\right), \quad (8)$$

$$4\pi^2\nu^2/c^2=E=(\pi n/L)^2+(\rho_{im}/a)^2, \quad (9)$$

where ρ_{im} is the ith root of $J_m'(x)=0$. n and m are positive integers or zero. For fixed m these roots differ by approximately π, except that the first root is always greater than m. We wish to know the number of solutions less than some E, or what is the same thing, of the infinitely many possible combinations of n, m, and i, how many yield values of (9) which are less than a given E? The first step in the solution is to hold E, n, and

[4] F. V. Hunt, L. L. Beranek and D.-Y. Maa, J. Acous. Soc. Am. **11**, 80 (1939).
[5] D.-Y. Maa, J. Acous. Soc. Am. **10**, 235 (1939).
[6] R. H. Bolt, J. Acous. Soc. Am. **10**, 228 (1939).

[7] $\sum_{n=1}^{N}n^k=N^{k+1}/(k+1)+\frac{1}{2}N^k+kN^{k-1}/12+\cdots$.

[8] K. Husimi, Proc. Phys. Math. Soc. Japan **21**, 759 (1939).

m fixed and determine $S_m(\rho_0)$, the number of roots of $J_m'(x)=0$ which are less than ρ_0. ρ_0 is chosen as the first root of the m_0th order Bessel function, there being no roots $<\rho_0$ for $m>m_0$.

Debye's asymptotic formula for the Bessel function, valid for large x, is[9]

$$J_m(x)\leqq(2/\pi s)^{\frac{1}{2}}(F_1\cos\varphi+F_2\sin\varphi), \quad (10)$$

$$s^2=x^2-m^2, \quad \varphi=s-m\arctan(s/m)-\pi/4. \quad (11)$$

F_1 and F_2 are semi-convergent power series in s and m. To the degree of accuracy required here they are[9]

$$F_1=1-0(m^4/s^6) \qquad F_2=0(m^2/s^3).$$

Setting the derivative of (10) equal to zero gives

$$\tan\varphi=(m^2+s^2)/2s^3+0(m^2/s^3)$$

or

$$\varphi=(k-1)\pi+0(m^2/s^3), \quad (12)$$

where k is the order number of the root. Solving for k and putting $m=\rho_0\cos\tau_0$ gives for the number of roots less than ρ_0,

$$S_m(\rho_0)=(\sin\tau_0-\tau_0\cos\tau_0)\rho_0/\pi+\tfrac{3}{4}-0(m^2/s^3). \quad (13)$$

We now allow m to vary and find the total number of roots less than ρ_0 for all values of m and i.

$$N(\rho_0)=\sum_{m=0}^{m_0}S_m(\rho_0)$$

$$=\sum_{m=0}^{m_0}\left\{\frac{\rho_0}{\pi}(\sin\tau_0-\tau_0\cos\tau_0)+\tfrac{3}{4}-\theta\right\}-R. \quad (14)$$

R is the contribution of the term in m^2/s^3. It is of the order of magnitude of $\rho_0^{\frac{1}{2}}$. θ is the average value of

$$\epsilon=S_m(\rho_0)-[S_m(\rho_0)],$$

that is, the difference between $S_m(\rho_0)$ and the largest integer included in $S_m(\rho_0)$. The expansion of $S_{m-\sigma}(\rho_0)$ in a Taylor's series about $S_m(\rho_0)$ furnishes the values of ϵ over a small range of σ, and setting $\theta=\epsilon_{\text{average}}$ gives $\theta=\frac{1}{2}+0(1/\rho_0)$. Equation (14) is now summed by expanding in powers of m and using Euler's summation formula. Reduction of the series to closed form and substitution of[10]

$$m_0=\rho_0-0.8086\rho_0^{\frac{1}{3}}+\cdots$$

gives

$$N(\rho_0)=\rho_0^2/8+(\tfrac{1}{4}+\tfrac{1}{2}\pi)\rho_0+0(\rho_0^{\frac{1}{3}}). \quad (15)$$

Now when $m\neq0$, the solutions of (8) are doubly degenerate, so we must multiply (15) by two and substract the number of roots for $m=0$, or ρ_0/π.

$$2N(\rho_0)-S_0(\rho_0)=\rho_0^2/4+\rho_0/2+\cdots. \quad (16)$$

Returning to (9), the number of solutions of

$$E\geqq(n\pi/L)^2+(\rho_{im}/a)^2$$

for fixed n is given by (16) if we put

$$\rho_0=a(E-\pi^2n^2/L^2)^{\frac{1}{2}}. \quad (17)$$

Summed over n,

$$N(E)=\sum_{n=0}^{LE^{\frac{1}{2}}/\pi}\{\tfrac{1}{4}\rho_0^2+\tfrac{1}{2}\rho_0\}. \quad (18)$$

$$N(E)=\frac{1}{6\pi}a^2LE^{\frac{3}{2}}+\tfrac{1}{8}(a^2+aL)E+\cdots. \quad (19)$$

Or, with $V=\pi a^2L$ and $A=2\pi a^2+2\pi aL$,

$$N(\nu)=\frac{4\pi V\nu^3}{3c^3}+\frac{\pi A\nu^2}{4c^2}+\cdots. \quad (20)$$

Of these normal modes, the number with grazing incidence on the end walls, $(n=0)$, is $(\pi a\nu/c)^2+\pi a\nu/c$, and the number with grazing incidence on the side walls $(m=0,\ \rho_0=0)$ is $2L\nu/c$.

III. Sphere

For a sphere of radius r_0, the wave functions are

$$\psi=\frac{1}{\rho^{\frac{1}{2}}}J_{n+\frac{1}{2}}(\rho)P_n^l(\cos\theta)e^{il\phi}, \quad (21)$$

$$\rho=\frac{r}{r_0}\rho_{jn}, \quad E_{jn}=\frac{\rho_{jn}^2}{r_0^2}, \quad l=0,\pm1,\pm2,\cdots\pm n$$

with ρ_{jn} the jth root of

$$\frac{d}{d\rho}\left\{\frac{1}{\rho^{\frac{1}{2}}}J_{n+\frac{1}{2}}(\rho)\right\}=0. \quad (22)$$

Let $T_n(\rho_0)$ be the number of roots of (22) less than $\rho_0=\rho_{1n_0}$, the first root for $n=n_0$. There will

[9] E. Jahnke and F. Emde, *Funktionentafeln* (Teubner, Leipzig, 1938), p. 139.

[10] Reference 9, p. 143.

be no roots $<\rho_0$ for $n>n_0$. Since each root gives $2n+1$ solutions of the same frequency,

$$N(E)=\sum_{n=0}^{n_0} T_n(\rho_0)(2n+1), \quad E=\rho_0^2/r_0^2. \quad (23)$$

By Debye's formula, the solutions of (22) are

$$\varphi=\pi\{T_n(\rho_0)-1\}$$
$$+\arctan\left\{\frac{1}{2s}\left(1+\frac{\rho_0^2}{s^2}\right)+0\left(\frac{m^2}{s^3}\right)\right\}. \quad (24)$$

The contribution of the last term to the final result is not greater than $0(\rho_0^{4/3})$, and it will therefore be dropped.

$$T_n(\rho_0)=\varphi/\pi+1=s/\pi$$
$$-(m \arctan s/m)/\pi+\tfrac{3}{4}-\theta \quad (25)$$

where $m=n+\frac{1}{2}$. θ is the correction factor to allow for the difference between the calculated value of $T_n(\rho_0)$ and the next lowest integer. It is evaluated as in Section II and has the value $\frac{1}{2}+0(1/\rho_0)$. When $T_n(\rho_0)$ is expanded in powers of n, inserted in (23) and summed, the result is[11]

$$N(E)=2\rho_0^3/9\pi+\rho_0^2/4+\cdots. \quad (26)$$

With $\rho_0=2\pi r_0\nu/c$, $V=4\pi r_0^3/3$, $A=4\pi r_0^2$,

$$N(\nu)=4\pi V\nu^3/3c^3+\pi A\nu^2/4c^2+\cdots. \quad (27)$$

IV. Prism, Half-Cylinder, and Half-Sphere

It may be noted from (3) that if $L_x=L_y$ each normal frequency is doubly degenerate, provided that $n_x\neq n_y$. That is, interchanging n_x and n_y yields a new wave function having the same frequency. The linear combination of these two wave functions—

$$\Phi=\cos(n_z\pi z/L_z)[\cos(n_x\pi x/L_x)$$
$$\times\cos(n_y\pi y/L_x)+(-1)^{n_x-n_y}$$
$$\times\cos(n_y\pi x/L_z)\cos(n_x\pi y/L_z)], \quad (28)$$

satisfies the boundary condition $\partial\Phi/\partial n=0$ for the volume bounded by the planes $z=L_z$, $y=L_x-x$, and the coordinate planes, i.e., for a 45° prism. A distinct solution is obtained for each n_x, $n_z=0, 1, 2, \cdots$, and each $n_y=0, 1, 2, \cdots n_x$. The number of solutions $N(\nu)$ may be obtained by the method of Section I with the restriction $n_y\leqq n_x$.

If in Eq. (8) only the cosine term is used the wave functions satisfy the boundary conditions on the plane $\phi=0, \pi$, that is, in a half-cylinder. $N(\nu)$ may be found by replacing (16) by (15) in the summation.

Similarly, the result for a half-sphere is found by restricting the values of l in (21) to positive integral values or zero.

$N(\nu)$ for all three cases is the same.

$$N(\nu)=4\pi V\nu^3/3c^3+\pi A\nu^2/4c^2+\cdots. \quad (29)$$

It is evident that the method can be extended to various sectors of cylinders and spheres by suitable restrictions on l and m. Let us note that in passing from the perfect symmetry of the sphere to the lower symmetry of the other enclosures there is no hint of a change in the coefficient of A in Eq. (29). It would be interesting if it were possible to prove rigorously that (29) holds for an enclosure of arbitrary shape.

In case the walls are not rigid the boundary conditions for the wave equation are changed to

$$\partial\psi/\partial n+\mu\psi=0$$

with a corresponding change in the frequency of the normal modes. For small absorption the frequency will be decreased and $N(\nu)$ will be larger than that given by (29).

When the analysis of the preceding sections is carried through for $\psi=0$ on the boundary, the number of solutions with frequency less than ν is found to be

$$4\pi V\nu^3/3c^3-\pi A\nu^2/4c^2+\cdots \quad (30)$$

for all of the above enclosures.

V. Resonance Response and Sound Decay in a Cylinder

Of the above shapes the cylinder has been selected for the calculation of the sound decay because it retains some of the symmetry properties of the rectangle and the solution should, therefore, show some of the same characteristics as that of the rectangle. The analysis given here will parallel that given by Morse[12] and by Hunt,

[11] $n_0+1/2=\rho_0-B\rho_0^{\frac{1}{3}}$. $B\leqq 0.81$, although the first two terms of (26) are independent of B.

[12] P. M. Morse, *Vibration and Sound* (McGraw-Hill Book Company, Inc., New York, 1936), Chapter VIII.

Beranek, and Maa[4] for a rectangular enclosure.

If the sth normal mode ψ_s has a damping factor K_s and angular frequency ω_s, the wave equation may be written

$$\nabla^2\psi_s=[(i\omega_s+K_s)/c]^2\psi_s. \tag{31}$$

It will be assumed that the damping is so small that the wave functions and the frequencies are given sufficiently accurately by the undamped values.

$$\psi_s \cong \frac{\exp(\pm im\phi)\cos(n\pi z/L)J_m(\rho_{im}r/a)}{J_m(\rho_{im})[1-m^2/\rho_{im}^2]^{\frac{1}{2}}}, \tag{32}$$

$$\iiint \psi_s^2 dV = V/4\sigma_s. \tag{33}$$

Here $\sigma_s=\sigma_n\sigma_m$. σ_m is 1 if $m\neq 0$, and equals $\frac{1}{2}$ if $m=0$. σ_n is defined similarly in terms of n. Let there be a source in the chamber described by the source function

$$q=Q(r,\phi,z)e^{-2\pi i\nu t}, \tag{34}$$

giving rise to a pressure

$$p=P(r,\phi,z)e^{-2\pi i\nu t}. \tag{35}$$

Both the known function Q and the unknown pressure amplitude function P may be expanded in terms of the orthogonal set ψ_s.

$$Q=\sum_s B_s\psi_s, \quad B_s=(4\sigma_s/V)\iiint Q\psi_s dV, \tag{36}$$

$$P=\sum_s C_s\psi_s. \tag{37}$$

When Q is axially symmetrical B_s is zero unless $m=0$. This special case is treated by Beranek[13] without making the assumption that the damping effect on the wave functions is small.

For the steady state p must satisfy

$$\nabla^2 p-\frac{1}{c^2}\frac{\partial^2 p}{\partial t^2}=-\rho_0\frac{\partial q}{\partial t}. \tag{38}$$

Insertion of Eqs. (31) and (34–37) and comparison of the coefficients of ψ_s gives

$$C_s=\frac{2\pi i\nu\rho_0 c^2 B_s}{(i\omega_s+K_s)^2+(2\pi\nu)^2}. \tag{39}$$

[13] L. L. Beranek, J. Acous. Soc. Am. **11**, 3 (1940).

For small absorption $K_s\ll\omega_s$, and K_s^2 may be neglected. Let the source be a point source of strength Q_0 at S_0.

$$C_s=\frac{4\rho_0 c^2}{V}\cdot\frac{2\pi\nu Q_0\psi_s(S_0)\sigma_s}{2\omega_s K_s+i[\omega_s^2-(2\pi\nu)^2]}. \tag{40}$$

The mean energy density W_0 is

$$W_0=\frac{1}{V}\iiint\frac{p^2}{2\rho_0c^2}dV=\frac{1}{8\rho_0c^2}\sum_s C_s^2\frac{1}{\sigma_s}. \tag{41}$$

The outward rate of flow of energy across unit area from the sth mode is $p_s'U_s$. U_s is the particle velocity normal to the boundary and p_s' is the true pressure for the sth mode. $p_s'=p_s+h_s$, where for large impedance h_s is small compared to p_s. Since the normal impedance coefficient is defined as $Z=p_s'/U_s$ the rate of flow of energy becomes $p_s'^2/Z\cong p_s^2/Z$. The time average of the rate of flow of energy across the boundary is then

$$-\frac{dW_{0s}}{dt}=\frac{1}{2}\iint\frac{1}{Z}p_s^2dA=\frac{1}{2}C_s^2\iint\frac{1}{Z}\psi_s^2dA. \tag{42}$$

Let the ends of the cylinder have impedance Z_1, and the sides Z_2. (If the impedances of the two ends are different, replace $1/Z_1$ by $(\frac{1}{2}Z_1+\frac{1}{2}Z_1')$ in the final result.) Integration of (42) and substitution from (41) gives

$$-\frac{dW_{0s}}{dt}=W_{0s}4\rho_0c^2\times\left(\frac{\sigma_n}{LZ_1}+\frac{1}{2aZ_2[1-(m/\rho_{im})^2]}\right) \tag{43}$$

or, since the energy decays as $\exp(-2K_st)$,

$$K_s=2\rho_0c^2\left\{\frac{\sigma_n}{LZ_1}+\frac{1}{2aZ_2[1-(m/\rho_{im})^2]}\right\}. \tag{44}$$

Notice that the damping on the end walls is independent of the angle of incidence, except for grazing incidence, where it is reduced by a factor $\frac{1}{2}$. This is identical with the result for a rectangular room. The damping on the side walls increases with increasing number of radial nodal surfaces and decreases with increasing number of cylindrical nodal surfaces.

When the driving frequency is low only a few normal modes will be excited and the energy

density at a time t after the source is turned off must be calculated by direct summation of

$$W_0=\frac{1}{8\rho_0c^2}\sum_s\frac{C_s^2}{\sigma_s}\exp(-2K_st) \tag{45}$$

with the insertion of (40) and (44). For high frequencies many modes are excited and it is convenient to use the results of Section II. The presence of the term $1-(m/\rho_{im})^2$ in the damping factor, however, adds a complication not found in the rectangular case. The general method of attack will be illustrated by the following example.

Let the source be placed on the circumference at one end. Only one of the two modes for each value of m will be excited. From (40), C_s is small unless $2\pi\nu\leqq\omega_s$, so that for a warble band of frequency range ν_0 to $\nu_0+\Delta\nu$

$$C_s^2\leqq\frac{8\rho_0c^2R\psi_s^2(S_0)\sigma_s^2}{K_s^2}=\frac{8\rho_0c^2R\sigma_s^2}{K_s^2(1-x^2)} \tag{46}$$

if ω_s is in the range $2\pi\nu_0$ to $2\pi(\nu_0+\Delta\nu_0)$ and effectively zero for ω_s outside this range.[14] R is a constant and x is the ratio m/ρ_{im}. With the notation

$$\alpha=2\rho_0c^2/LZ_1,\qquad\beta=\rho_0c^2/aZ_2$$

(45) becomes

$$W_0=\sum_s\frac{R\sigma_s\exp[-2t\{\alpha\sigma_n+\beta/(1-x^2)\}]}{\{\alpha\sigma_n+\beta/(1-x^2)\}^2(1-x^2)}. \tag{47}$$

The analysis of Section II must now be repeated with the restriction $m/\rho_{im}\leqq x$. It is found that, to a first approximation, the number of roots satisfying this condition is a linear function of x. x ranges from 0 to $1-\delta$, where δ is much less than unity, but since the contribution to W_0 is zero for $x=1$, the range will be taken as 0 to 1. The final summed results for the number of modes with frequencies (nondegenerate) in the range ν_0 to $\nu_0+\Delta\nu$, and m/ρ_{im} in the range x, dx, are

$$M_{m,0}(\nu_0\Delta\nu)dx=\pi^2a^2(\nu_0\Delta\nu/c^2)dx,\quad(n=0), \tag{48}$$

$$M_{0,n}(\nu_0\Delta\nu)=2\pi aL\nu_0\Delta\nu/c^2,\quad(m=0), \tag{49}$$

and if neither m nor n is zero,

$$M_{m,n}(\nu_0\Delta\nu)dx=2\pi^2a^2L\frac{\nu_0^2\Delta\nu}{c^3}\left[1-\frac{c}{4\nu_0}\left(\frac{1}{L}-\frac{1}{a}+\frac{2}{\pi a}\right)\right]dx. \tag{50}$$

In all cases terms in $\Delta\nu$ have been dropped as negligible compared to $\nu_0^2\Delta\nu$ and $\nu_0\Delta\nu$. Let

$$F(\alpha,\beta,t)=\int_0^1\frac{\exp\{-2[\alpha+\beta/(1-x^2)]t\}dx}{[\alpha+\beta/(1-x^2)]^2(1-x^2)}. \tag{51}$$

For large values of t, the integrand, with the substitution $(1-x^2)^{-1}=1+y$, may be expanded in an asymptotic series and integrated in terms of gamma-functions.

$$F(\alpha,\beta,t)\leqq\frac{\pi^{\frac{1}{2}}\exp[-2(\alpha+\beta)t]}{2(\alpha+\beta)^2(2\beta t)^{\frac{1}{2}}}\left[1-\left(\frac{1}{2(\alpha+\beta)}+\frac{1}{8\beta}\right)t^{-1}+\left(\frac{9}{16(\alpha+\beta)^2}+\frac{9}{128\beta^2}+\frac{3}{16\beta(\alpha+\beta)}\right)t^{-2}+\cdots\right]. \tag{52}$$

This series is not convergent and is valid only for large t. When t is small,

$$F(\alpha,\beta,t)=\left[\frac{2\alpha+\beta}{2[\alpha(\alpha+\beta)]^{\frac{3}{2}}}\sinh^{-1}\left(\frac{\alpha}{\beta}\right)^{\frac{1}{2}}-\frac{1}{2(\alpha+\beta)\alpha}\right]-\left[\frac{2}{[\alpha(\alpha+\beta)]^{\frac{1}{2}}}\sinh^{-1}\left(\frac{\alpha}{\beta}\right)^{\frac{1}{2}}\right]t+\cdots. \tag{53}$$

[14] Equation (46) holds only if $\Delta\nu$ is much less than the width of a resonance band, that is, if $\Delta\nu\ll K_s/\pi$. If this condition does not hold, (46) must be replaced by (55).

Substitution of these results in (47) gives as the final formula for the mean energy density

$$W_0/R=M_{m,n}(\nu_0\Delta\nu)F(\alpha,\beta,t)+\tfrac{1}{2}M_{n,0}(\nu_0\Delta\nu)F((\alpha/2),\beta,t)+\tfrac{1}{2}M_{0,n}(\nu_0\Delta\nu)(\alpha+\beta)^{-2}\exp[-2(\alpha+\beta)t]. \quad (54)$$

The constant R may be adjusted to make $W_0=1$ at $t=0$.

When the width $\Delta\nu$ of the source is so wide that the response peak of the normal mode lies entirely within the band[14] the excitation of the normal mode is proportional not to the height but to the area of the response peak. Since the height varies as $1/K_s^2$ and the width as K_s the area varies approximately as $1/K_s$ and (46) becomes

$$C_s^2=8\rho_0c^2R\sigma_s^2/K_s(1-x^2). \quad (55)$$

Equation (54) must in this case be changed to read

$$W_0/R=M_{m,n}(\nu_0\Delta\nu)G(\alpha,\beta,t)+\tfrac{1}{2}M_{m,0}(\nu_0\Delta\nu)G((\alpha/2),\beta,t)+\tfrac{1}{2}M_{0,n}(\nu_0\Delta\nu)(\alpha+\beta)^{-1}\exp[-2(\alpha+\beta)t], \quad (56)$$

where $G(\alpha,\beta,t)$ is a function defined by

$$G(\alpha,\beta,t)=\int_0^1\frac{\exp[-2t(\alpha+\beta/(1-x^2))]dx}{\alpha(1-x^2)+\beta} \quad (57)$$

and α and β are defined as in (47). For large t,

$$G(\alpha,\beta,t)=\frac{\pi^{\frac{1}{2}}\exp[-2(\alpha+\beta)t]}{2(\alpha+\beta)(2\beta t)^{\frac{1}{2}}}\left[1-\left(\frac{1}{8\beta}+\frac{1}{4(\alpha+\beta)}\right)\frac{1}{t}+\left(\frac{9}{128\beta^2}+\frac{3}{32\beta(\alpha+\beta)}+\frac{3}{16(\alpha+\beta)^2}\right)\frac{1}{t^2}+\cdots\right] \quad (58)$$

and at $t=0$,

$$G(\alpha,\beta,0)=[\alpha(\alpha+\beta]^{-\frac{1}{2}}\tanh^{-1}\left(\frac{\alpha}{\alpha+\beta}\right)^{\frac{1}{2}}. \quad (59)$$

Similar results may be obtained for any of the shapes listed in the first four sections, for an arbitrary position of the source. In most cases it will be found that the absorption depends on some parameter x, corresponding to m/ρ_{im} in the cylindrical case. This leads to the consideration of an integral similar to (51). If this is a complicated function, it may be more convenient to sum over a small number of ranges of x, using an average value of x for each range.

When the results for the rectangle, cylinder, sphere, half-cylinder, half-sphere, 45° prism, and the pyramid formed by a 1–1–1 cut from a cube are compared, one notes several similarities in the formula for the damping constant K. One or more symmetry factors σ_i always appear in K when the surface contains one or more plane surfaces A_i. Furthermore, the number of modes for which σ_i is $\frac{1}{2}$ is $2\pi A_i\nu_0\Delta\nu/c^2$, if A_i is one of a symmetrical pair of surfaces, and otherwise $\pi A_i\nu_0\Delta\nu/c^2$. If now, one *assumes* that the above rule holds for all shapes, and that Eq. (29) holds for all shapes, it is possible to derive certain simple corrections to Sabine's law which are applicable to rooms of arbitrary shape. However, the weakness of these assumptions, plus the likely presence of terms corresponding to $x=m/\rho_{im}$ in K make it seem almost certain that such corrections are meaningless.

I wish to thank Dr. Bardeen and Dr. Hill for their helpful interest and suggestions.

A Continuously Variable Acoustic Impedance

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IN MANY applications in acoustics it would be desirable to have an acoustic impedance whose magnitude and phase angle could be easily and continuously adjusted. Such an application, for example, is the termination of a sound tube in its characteristic impedance, Z_0, to eliminate the reflected wave. The usual method of doing this is to add a long length of tubing having tufts of fur or wool distributed along its length to absorb the incident sound. In practice it is very difficult to obtain even a fair approximation to Z_0 by this method. It has, besides, the disadvantage that it is not possible to reproduce accurately any setting so that cut-and-try becomes tedious. For this reason the acoustic impedance of Fig. 1 was devised. It utilizes the fact that an acoustic resistance may be obtained by allowing a tube or pipe to radiate the incident energy through small holes along its length. However, these holes will also have the effect of adding shunt acoustic inductance[1] to the circuit. In this particular case a pure resistance is desired so the inductance must be tuned out with an equal and opposite capacitive reactance. This capacitive reactance may be conveniently obtained by closing the terminating section (which is less than a quarter-wave-length long) by a sliding rod which adds an adjustable acoustic capacity. This provides the means for making the termination a pure resistance. The magnitude of this resistance is varied by using two close-fitting concentric tubes, as shown, with an identical arrangement of holes. By sliding the outer tube round the inner one it is possible to change both the number and size of the holes through which radiation occurs. The change in number varies both the inductance and resistance while the change of size varies the ratio of inductance to resistance. Using these three adjustments it is a simple matter to obtain a nearly perfect match.

In practice, radiation from the termination is usually undesirable, so the entire terminating section is covered with a closed-end copper tube having a diameter considerably larger than that of the radiating tube, and the space between these tubes is filled with absorbent wool. The resulting increased back-pressure at the radiating holes generally requires a slight change in the adjustment but this is readily made.

This impedance unit can be constructed to cover a fairly wide range of values and should find a measure of usefulness in the acoustics field.

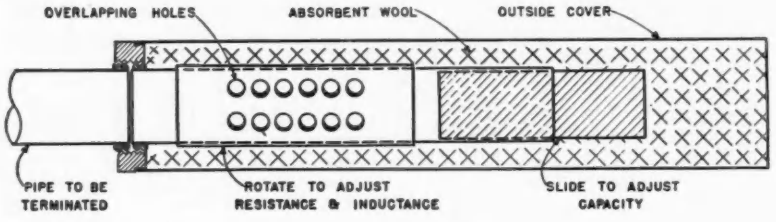

FIG. 1.

[1] See, for example, *Vibration and Sound* by Philip M. Morse (McGraw-Hill Book Company, Inc., New York, 1936), p. 205. The effect on acoustic lines is shown in a Bulletin, "Acoustic models of radio antennas," to be published shortly by the Engineering Experiment Station of The Ohio State University.

A Sound Measurement Room Utilizing the Live End-Dead End Studio Principle

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(Received April 10, 1941)

The requirements of a suitable sound test room for the measurement and analysis of sound produced by household appliances are discussed. It is shown that neither the highly reverberant room nor the highly absorptive room will meet all requirements due to the room resonant response of the former and the high sensitivity to directional effects of the latter. A sound room is described which makes use of a reflective floor, absorptive walls and a highly absorptive ceiling with the microphone placed near the ceiling. The sound source is moved in a reciprocating manner and a sound diffuser is rotated slowly during measurements to average out the space pattern effects. A high degree of sound reduction through the walls is achieved by massive construction and a large reduction of transmitted vibration is effected by a coil spring suspension. The test room has been used over an extended period of time and has been of great assistance in sound analysis investigations directed toward sound reduction on electric cleaners.

INTRODUCTION

IT is well known that one of the chief problems encountered in the field of industrial noise measurements is the provision of a test environment for the sound source and microphone that is similar to that which exists for the listener. In many cases it is very difficult to establish a representative test condition such as, for example, for equipment that may be operated in enclosures of widely differing acoustic properties. Under these conditions a test condition may be arbitrarily selected and standardized with the assumption that a reproducible test environment has been established and any variation from predetermined limits may be quickly determined. In other cases the acoustic properties of the enclosure have a large influence on the effective sound heard by the user of the equipment in question. This problem is generally encountered in sound level measurements of household appliances and the electric cleaner is an example of an appliance that may be used under conditions varying from very highly absorptive to highly reverberant surroundings.

The method by which a sound test room for electric cleaners was developed in the Hoover Engineering Laboratories may be of interest due to the nature of the acoustic problems encountered. No novelty is claimed for the particular test room finally developed since many phases of the problem have been discussed by various investigators in the literature. The problem has been approached largely from considerations of objective sound measurement technique since subjective methods are not well suited to sound analysis.

IDEALIZED TEST ROOM

The ideal sound test room, from the standpoint of objective sound measurements, would be one in which the acoustic response of the room as measured at the microphone with constant acoustic power input to the room would be independent of the frequency throughout the audible range and also independent of the orientation and position of the sound source in the room. Obviously, such a room cannot exist for a sound source and room of finite dimensions since the requirements of diffuse sound distribution and uniform frequency response are incompatible. It has been shown by several investigators[1,2] that the acoustic response of a reverberant room may be explained by treating the room as a system of acoustic resonators whose natural frequencies are related to the velocity of sound in the enclosed volume of air and to the separation of reflecting surfaces within the room, and whose damping characteristics are determined by the acoustic absorption of the reflecting surfaces and of the gas volume enclosed in the room. Consequently, the highly reverberant "live" room will have an acoustical response that is

[1] V. O. Knudsen, J. Acous. Soc. Am. **4**, 20 (1932).
[2] P. H. Morse, J. Acous. Soc. Am. **11**, 56 (1939).

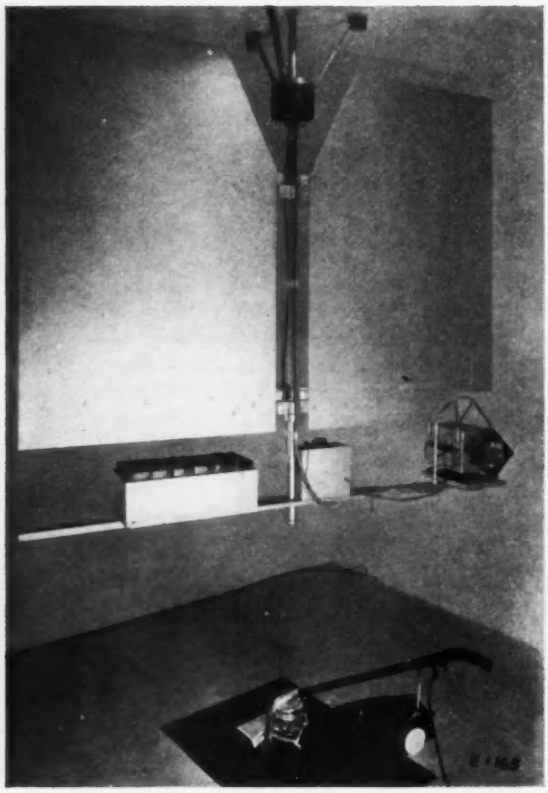

FIG. 1. Original reverberation room showing rotating two-blade sound diffuser and microphone assembly.

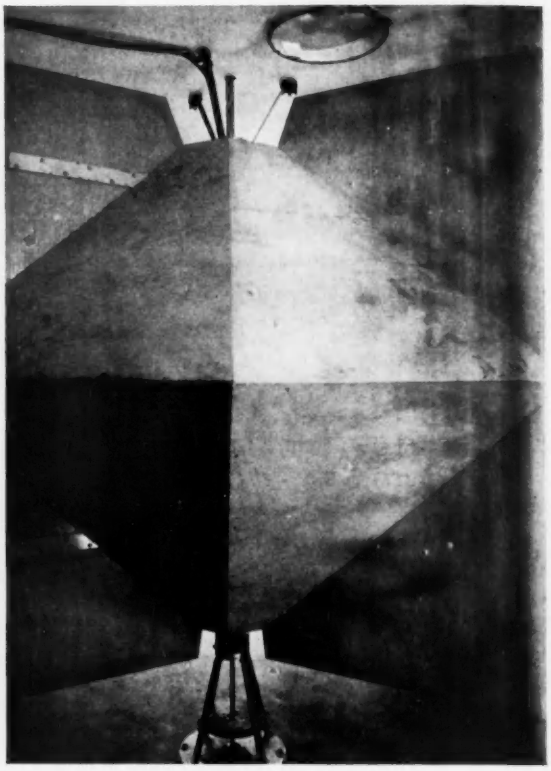

FIG. 2. Original reverberation room with rotating tri-pyramid sound diffuser.

very irregular as the frequency is varied but will provide an excellent means of nearly eliminating the variation of acoustic response with direction and position of the sound source. Knudsen[1] reported in 1932 that certain low frequency components may be intensified by as much as 20 to 25 db by room resonance.

The highly absorptive "dead" room has been shown to provide almost complete freedom from variation of intensity with frequency[3] but has the limitation of large variations of intensity with position and direction of the sound source. The sound integration method described by Hanson and Boardman[4] for determining the acoustic power of a high frequency sound source under "dead" room conditions appears to integrate almost completely the sound intensity over a hemisphere but would be a laborious method for frequency analysis and in addition this method seems best adapted to sound sources of relatively small dimensions. It can be seen that a room embodying certain features of the "live" room and of the "dead" room may, under certain circumstances, be an approach to the ideal sound test room. The live end-dead end studio used in radio broadcasting networks embodies several desirable features but is considered by some investigators to be undesirable for certain types of studio program pick-up. However, this type of room has been found to offer a number of advantages in sound measurement for reasons which will be discussed in a later section.

FUNDAMENTAL CONSIDERATIONS

A consideration of the nature of acoustic wave propagation in a gaseous medium will show that for the most part the wave fronts of sound waves emitted by household appliances approach a spherical shape. However, it is evident that the standing wave system excited by a sound source

[3] E. H. Bedell, J. Acous. Soc. Am. **8**, 118 (1936).
[4] R. L. Hanson and E. M. Boardman, "Apparatus for measuring the total sound power radiated by small sound sources," J. Acous. Soc. Am. **12**, 461A (1941).

emitting spherical waves in a sound measuring room with reflecting boundaries is largely of a plane wave nature with planes of pressure maximum at the boundaries and at various places throughout the room depending on the relation of the wave-length of the sound to the dimensions of the room. Consequently, the selection of a sound absorbing material for application to the boundaries of a room must take into consideration the sound absorbing coefficients for normal incidence as well as those for random incidence usually considered in reverberation room theory.

The choice of a microphone must likewise be guided by considerations of its polar response characteristic since this determines the ratio of normal to random incidence response. It would appear that the use of a combination pressure type and velocity type microphone with output voltages integrated by a thermocouple as described by Olson and Massa[5] and Wolff and Massa[6] would result in a more complete integration of the energy density existing in a strongly excited standing wave pattern wherein the pressure and velocity maxima occur at quarter-wave separations along the path of wave propagation. However, the limited overload capacity of the thermocouple and the necessity of using four microphones, one pressure type and three velocity type, does not permit this method to be readily adapted to industrial use. It is possible to obtain a measure of the sound energy density quite satisfactorily by the use of either a pressure or velocity type microphone provided that the space pattern is moved relative to the microphone or the microphone is moved relative to the space pattern through a distance of at least one-half wave-length. This may be accomplished in several ways such as: by rapidly shifting the frequency where possible by the use of the "warble tone"; by moving the sound source; by moving reflecting surfaces within the enclosure; or by moving the microphone. It has been shown[6] that the energy density in a reverberant room is relatively constant throughout the room despite large variations in pressure or velocity and consequently the combination pressure and velocity measurement would provide the most desired result if it were not for the limitations mentioned.

[5] H. F. Olson and F. Massa, *Applied Acoustics* (Blakiston's Son & Company, 1934), p. 261.

[6] I. Wolff and F. Massa, J. Acous. Soc. Am. **4**, 217 (1933).

Description of Sound Room

The sound test room as originally constructed in 1932 was a reverberation chamber of internal dimensions 14 ft. in length, 11 ft. in width and 10 ft. in height. The walls, ceiling and floor were constructed of reinforced concrete of a thickness not less than 9 in. and the entire room, weighing approximately 50 tons, was originally supported on cork which was later supplemented by a large number of coil springs in compression due to the excessive loading on the cork which reduced the elasticity. An inner steel vault door of $\frac{3}{8}$-in. thickness and a Celotex-treated outer wooden door permit access to the interior of the room. All electrical circuits were brought out of the room through flexible conduit and the mechanism for slowly rotating the sound diffusing reflector was located external to the room and mechani-

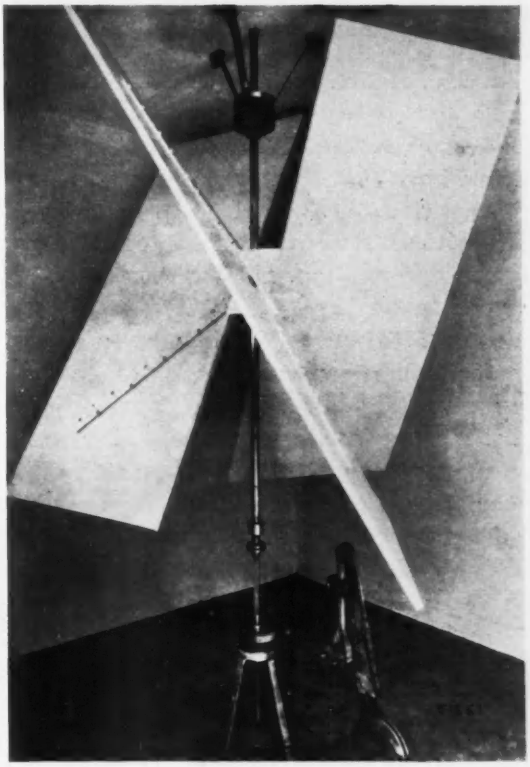

Fig. 3. Original reverberation room with rotating three-blade sound diffuser.

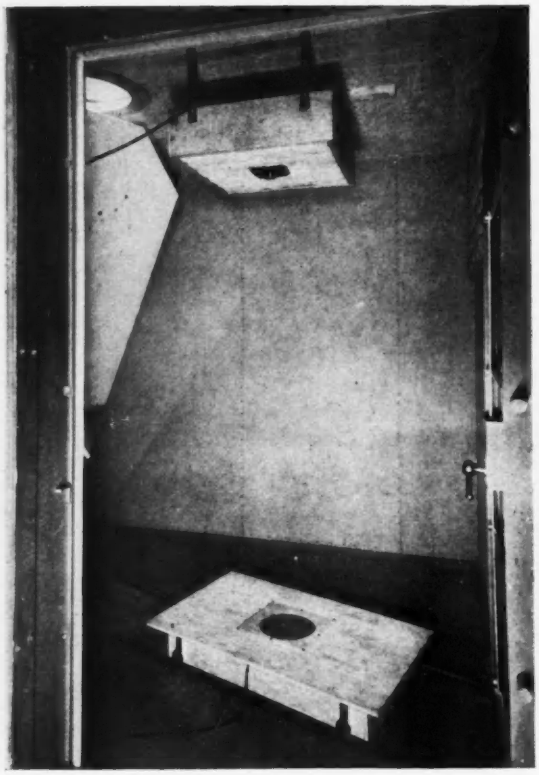

FIG. 4. Acoustically modified sound room with moving speaker and baffle used in response measurements.

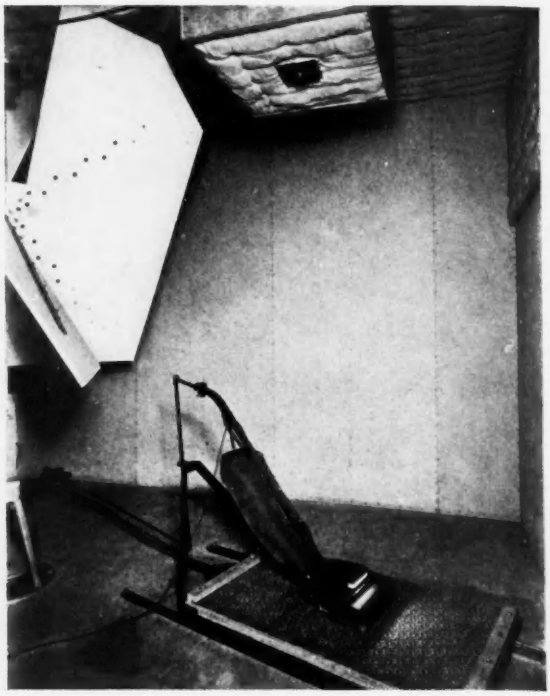

FIG. 5. Acoustically modified sound room with electric cleaner operating on moving platform device.

cally connected by means of a long leather belt having high elasticity. The interior wall and ceiling surface was very smooth and was provided with several coats of paint to provide very low sound absorption. The reverberation time of the original room was estimated to be of the order of 7 to 8 seconds. Figure 1 shows the interior of the room with a two-blade rotating steel sound diffuser and the previously used W.E. rotating condenser microphone assembly with battery supply for the single-stage microphone preamplifier. This photograph and others of the reverberation room were taken in 1932 and 1933.

A careful investigation of the frequency response of the original room with stationary RCA condenser microphone, using a loudspeaker with constant applied voltage placed on the floor of the room facing one end wall as a sound source, was made and very large fluctuations in the response curve with frequency (see Fig. 6) were observed making sound analysis very difficult. (The RCA microphone was used stationary due to the complexity of the 3-stage preamplifier.) Following the reasoning of Knudsen[1] the resonant frequencies of the room were calculated up to 344 cycles using the equation

$$n=\frac{c}{2}\left(\frac{p^2}{L_1^2}+\frac{q^2}{L_2^2}+\frac{r^2}{L_3^2}\right)^{\frac{1}{2}},$$

where n = the resonant frequency in cycles per second; c = velocity of sound in air; p, q, r are integers and L_1, L_2, L_3 are the lengths of the edges of the room. A total of 58 different resonant frequencies from the lowest one of 40 cycles to 200 cycles were calculated and of these nearly one-half of this group were identified in the response curve. An investigation was next conducted to determine the diffraction effects of large and specially shaped sound diffusing reflectors in an effort to reduce the resonant response conditions. Figures 2 and 3 show two of the experimental sound diffusers tested. The sound diffuser finally adopted is shown in Fig. 3 and this type appeared to be slightly superior to the others tested.

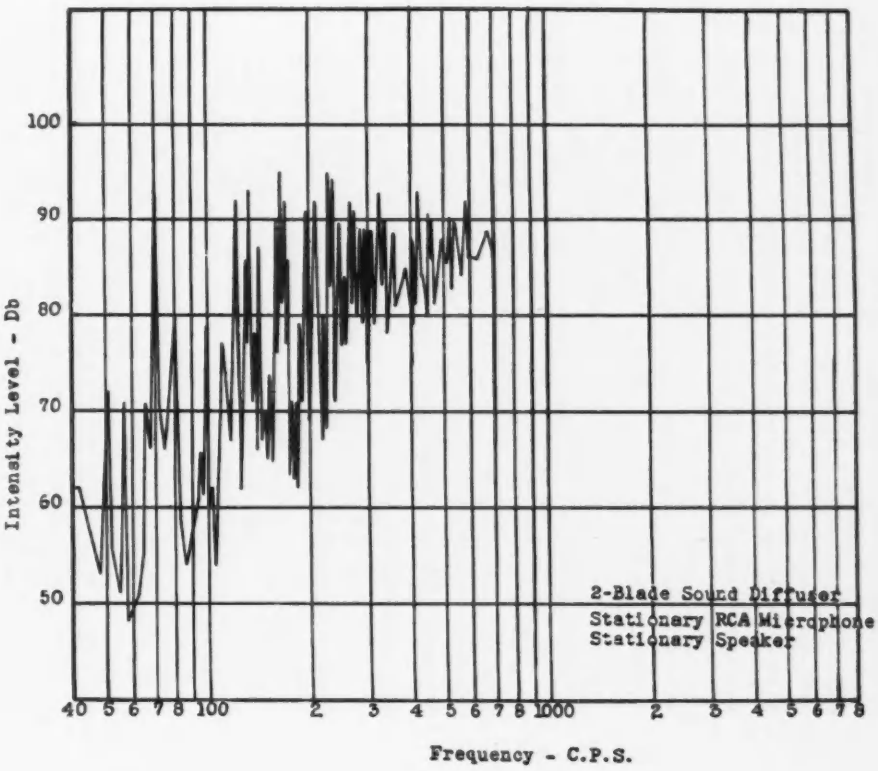

FIG. 6. Typical response of reverberation room before acoustical treatment.

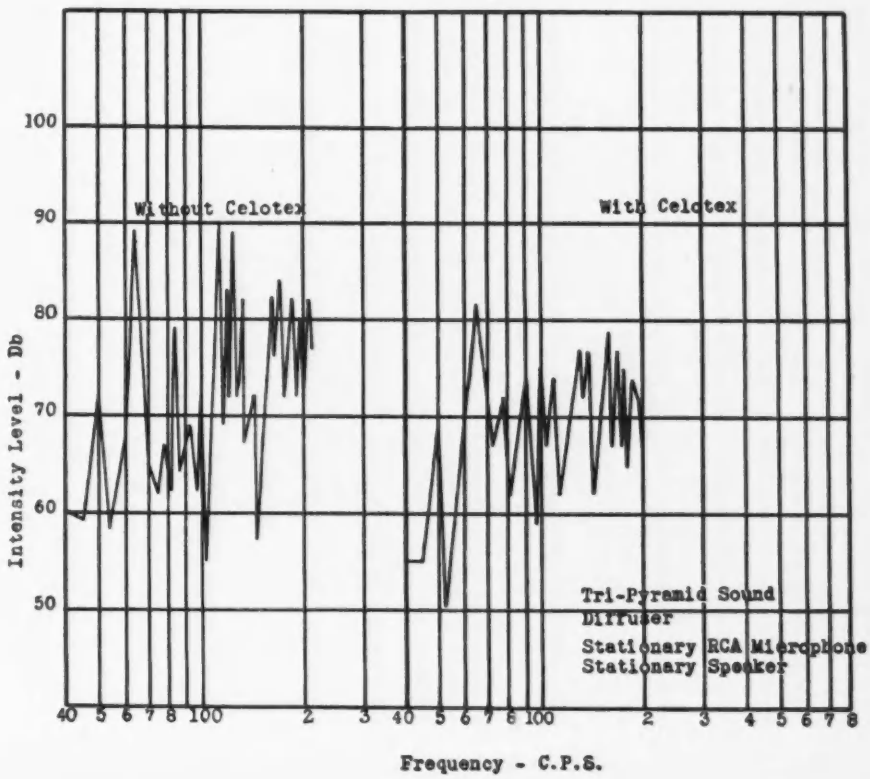

FIG. 7. Acoustical response of sound room with and without Celotex panels on side walls.

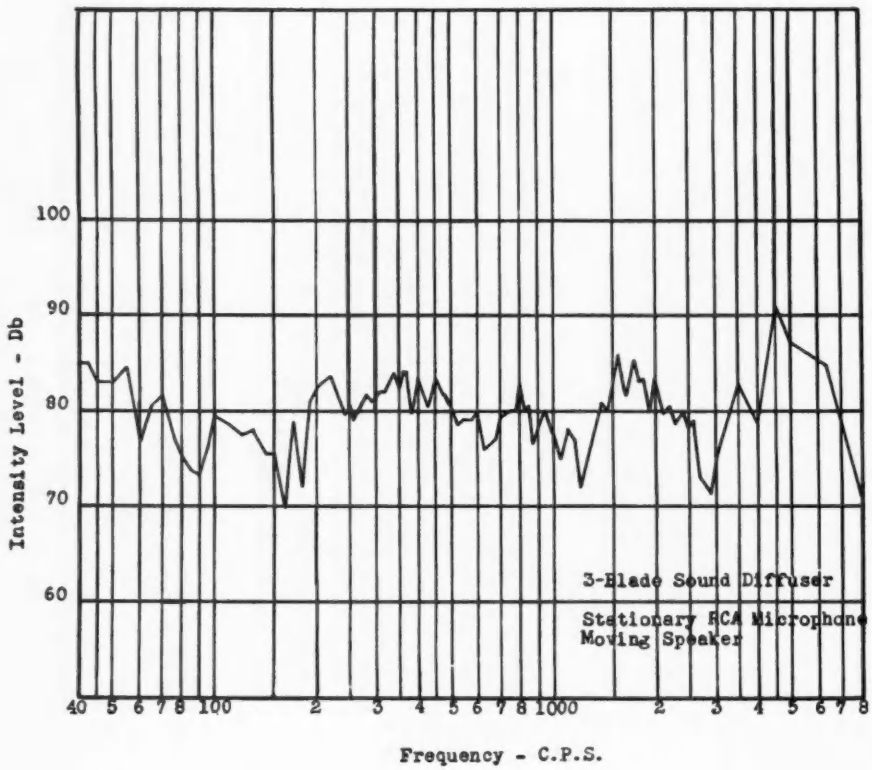

FIG. 8. Acoustical response of sound room with final modifications.

It is readily apparent from Fig. 6 that the typical reverberation room response was entirely too irregular for satisfactory analysis of low frequency sound and methods were next considered for the provision of acoustical absorption to reduce the response at resonance and also to broaden the resonance peaks. The first modification consisted of placing $\frac{1}{2}$-in. Celotex insulation panels against the side walls. Figure 7 shows the improvement in response characteristic obtained by this procedure. The next step consisted of permanently installing the Celotex panels by means of wood furring strips on the walls and ceiling. A definite improvement in characteristic was noted but additional absorption for the height resonant conditions was desirable. Consequently, a 2-in. layer of rock wool sound-absorbing blanket was applied to the ceiling and to upper sections of one side wall and one end wall. The room, as finally modified, is shown in Fig. 5 while Fig. 4 shows the loudspeaker and infinite baffle enclosure used in the measurement of the room response, substituted for the moving platform device. The moving platform is so arranged that a sound source such as an electric cleaner is operated in a reciprocating manner on the carpeted platform simultaneous with motion of the platform relative to the room. The RCA condenser microphone was placed in a baffle as this arrangement reduced certain undesirable responses in the higher frequency range due apparently to first reflections from the rock wool treated ceiling.

The speaker was placed in a horizontal plane with cone facing the microphone as this most nearly simulated actual operating conditions. Placement of the speaker on a reciprocating platform was found to reduce the effects of room response on speaker output as first discussed by Olson and Massa.[5] The response curve of the speaker was obtained by placing the microphone close to the speaker cone and the room measurements were corrected by this data. The final room response is shown in Fig. 8 and represents a very much more desirable test condition than was originally obtained using the reverberation room. The various stages of modification were completed in 1934 and there was very little precedence to follow at that time. However, several investigators have recently made an

extensive study of the acoustical response of enclosures having one or more bounding surfaces treated with sound absorptive material. Rettinger[7] found that rooms of irregular shape did not appear to possess discrete normal frequencies less sharp than those in rectangular rooms. Morse,[8] Beranek,[9] and Hunt, Beranek and Maa[10] also discussed various phases of this problem. Maa[11] concluded that the most effective positions for an absorbing material in a rectangular room are along the edges and especially the corners, where every normal mode of vibration has a maximum.

Conclusions

A sound measurement chamber has been developed for household appliance sound measurement and analysis which has the following properties:

(1) Room resonance effects have been greatly reduced by the use of sound absorbing materials and by placement of the microphone in a position that is located as near as possible to the pressure minima of the more important standing wave systems.

(2) A "live" floor-"dead" ceiling construction has been used to provide maximum diffusion of sound from directive sources and yet reduce undesirable resonance effects.

(3) Variation of sound intensity with separation of the moving source and stationary microphone has been minimized by provision of a constant separation during tests.

(4) Sound diffusion is provided by reverberation room effects, by the use of a rotating vane system and by the use of a reciprocating platform on which the sound source is placed.

(5) A large reduction of transmitted sound, 50 db or more, through the walls has been obtained while the natural frequency of the suspended room, 7 cycles per second, assures a very satisfactory reduction in transmitted vibrations of frequencies greater than 35 cycles. The basic sound level in the room is generally from 10 to 20 db and frequently is below the threshold of hearing.

The test room has been in use over a period of years and has been found to be quite satisfactory for the analysis of sounds extending from 50 cycles to 8000 cycles per second when using an appliance such as an electric cleaner which has several sound sources, some of which are quite directional. It is probable that the use of a directional microphone would simplify the room treatment but this was not practical at the time of modification since it was desired to continue the use of the RCA condenser microphone with the General Electric Sound Meter and Analyzer.

Acknowledgment

The authors are indebted to Dr. G. P. Daiger, Director of Laboratories of The Hoover Company, and to Messrs. G. N. DeMoss, T. A. Stoner and W. H. Tucker for their active participation in the earlier stages of the development of the present sound test room.

[7] M. Rettinger, Proc. I. R. E. **24**, 296 (1940).
[8] P. M. Morse, *Vibration and Sound* (McGraw-Hill Book Company, Inc., New York, 1936), p. 291.
[9] L. L. Beranek, J. Acous. Soc. Am. **12**, 14 (1940).
[10] Hunt, Beranek and Maa, J. Acous. Soc. Am. **11**, 80 (1939).
[11] D.-Y. Maa, J. Acous. Soc. Am. **12**, 39 (1940).

Theatrical Uses of the Remade Voice, Subsonics and Reverberation Control

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TO give maximum scope to the artist in the theater, he must be given as complete control over the auditory component of the show as he has over the visual component. Briefly, this means that the artist must have control over all sound from any source or sources, and that the audience shall hear such sound from any apparent source, or a moving source, or no apparent source, and that the sound may have any predetermined frequency characteristic, any absolute or relative intensity, and any degree of reverberation. The apparatus and technique by which such control may be achieved have been in process of development for a number of years and fill an increasingly important place in the theater as time goes on.

For a number of years, we have talked about using the remade voice, subsonics, and reverberation control. Because of present hazards attendant upon long range planning, we determined to test these phenomena at once in actual production, rather than explore them thoroughly and demonstrate next season. Accordingly, a series of experiments, consisting of the presentation of a number of episodes from well-known plays, was planned and carried out with the cooperation of a number of eminent people of the theater and opera, engineers and equipment manufacturers who contributed their time, counsel and talents most generously. The experiments were conducted in the Stevens Theater before three audiences. Criticism was solicited and enough has been received to make us fairly sure of what we have accomplished and what we have not.

There are many apparent demands in existing script for speech with characteristics other than those normally supplied by the human vocal apparatus. Many of you remember the voice we made for the Ghost in "Hamlet," accomplished by selective reproduction. The technique used in that instance has, however, the limitation that the only sound one has to work with is that which is present in the original voice which, obviously, will not do when one attempts to fulfill such a requirement as is set up for Ariel's speech in "The Tempest" when Alonso says,

> Methought the billows spoke, and told me of it;
> . . . and the thunder,
> That deep and dreadful organ-pipe, pronounc'd
> The name of Prosper.

Moreover, merely subtracting some frequencies from the voice and emphasizing others will not make it possible for a man to speak with the voice of an ass, as it seems that Bottom may logically do in "A Midsummer Night's Dream." Accordingly, we used the Vocoder to widen the scope within which we might remake the human voice. You are all familiar with the Vocoder and remember, no doubt, Mr. Vadersen's demonstrations. We tried the Vocoder first, to make voices for witches for the Witch Scenes in "Macbeth." Three voice qualities were set up on the machine—one with a fundamental pitch considerably above that of the soprano, one with a middle range and a quality somewhere between the sound of a rock crusher and a whiskey baritone, and the third, lower than a basso.

Audience reaction to the witches was favorable in that they succeeded in holding attention; unfavorable in that on commenting later, the audience generally complained of the fact that the witches seemed hard to understand. This condition is probably attributable in part to the unfamiliar substance of the lines.

The attempt to give unseen Ariel, in an episode from "The Tempest," the voice of a storm (thunder and wind) was more convincing to the audience, though handled with less technical skill. The voice of the actor was reproduced as faithfully as possible in the first speeches of the sequence, and then alternately used to modulate the sounds of wind and thunder.

In "A Midsummer Night's Dream," an ass's voice was provided for Bottom for the sequences in which he wears the ass's head. Significant

characteristics of an ass's bray seem to be, (1) an ass uses only vowels, (2) his fundamental frequency range is greater than that of a human voice, he produces his loudest sounds at the high and low ends of that range with little power in the middle, (3) he uses his whole range all the time. Once the Vocoder is set up to produce such a sound, almost anyone talking into it sounds like an ass. We mixed a small amount of the actor's original voice with the remade voice to preserve the identity of Bottom. The dubbing was accomplished by reproducing the voice from speakers upstage of the actor, and varying the output between speakers as the actor moved about the stage.

In Eugene O'Neill's "Lazarus Laughed," an attempt was made to give the laughter the musical quality and dynamic range prescribed for it. The laughter serves, in fact, as a musical accompaniment to the play and, in addition, motivates action and carries the final scene to its dramatic climax. We modulated a chord, played on an organ, with human laughter and accomplished variation by the relative amounts of voice and music used.

Inquiry has elicited the comments that the laughter was appreciated for its novelty and that it fitted into the production so well as to be accepted unquestioningly. I am inclined to feel that we only scratched the surface of what is possible with the play, and particularly the last scene which we used. Scoring all sound in the scene according to a musical pattern as we did for the dramatic episodes in the program of stereophonic recordings, and giving the laughter a varied instrumentation would, I am certain, enhance the effectiveness of the play beyond what has been possible heretofore.

All sequences involving the use of the Vocoder were recorded on vertically cut disks and reproduced from those disks in performance. The cueing which was very critical was accomplished by the use of the Fairchild Word Spotter.[1]

When we planned to use subsonics in a play we had the impression that we didn't know much about subsonics. That impression has now been amply confirmed. To make the job easy we took what seemed a simple problem, that of establishing the rhythm of the drum beat in "The Emperor Jones" as soon as the play starts which is some twenty minutes before the drum becomes audible, and achieving the nervous tension conventionally induced by making the drum loud, at an audible level so low as not to mask speech.

Signal sources and output transducers gave us trouble. Electronic wave generators gave audible harmonics. Strings with electrostatic pick-up would not go low enough. Conventional loudspeakers couldn't produce the requisite power at the appropriate frequency. A special unit, a cross between an organ pipe and a Helmholtz resonator was too big to get into the theater, and could not push out enough energy to be effective through the wall or the floor. Finally, we used a thunder screen[1] which produces a complex signal. We introduced a low-pass filter to eliminate frequencies above 16 cycles. Then we mounted speaker units directly on the under side of the floor. The speakers were machined out to make possible increased movement of the coil.

When the drum was to become audible the source was changed to a conventional thunder drum picked up by microphone, and speakers on-stage and in the house were added, but the subsonic channel was kept in operation and the shift was accomplished so gradually that there was no agreement in the audience as to when the drum became audible.

The technique of operation was varied from performance to performance partly because of the difficulty of monitoring. Members of the audience described their perception of the drum beat as a throbbing sensation in the forehead, as a rhythmic intermittent oppressed feeling, and the discontinuance of the drum at the end of the episode was generally described as the lifting of a weight from the chest.

Some members of the audience said they perceived nothing except the audible drum. Others were aware of the drum beat almost as soon as the curtain rose, and the actor who played Smithers, though claiming to feel nothing, spoke his lines in rhythm to the drum beat during one performance before the drum was audible. This fact is worthy of some note, since he has played the part many times, gives a

[1] H. Burris-Meyer, "Sound control apparatus for the theater," J. Acous. Soc. Am. 12, 122 (1940).

consistent interpretation, and has never before read his lines rhythmically.

At its best, the drum was most ominous and the audience reaction all that could be asked. At its worst, the drum was more effective than the conventional drum. The use of mechanical striking devices can make it consistent. We do not know the frequency pattern or the intensities used because of limitations of our test apparatus. The amplifiers had a total output rating of 400 watts. Moreover, it appeared that sounds which were unheard but distinctly felt could be distinguished by ear if the intensity were raised high enough. This phenomenon may have been caused by harmonics or by the fact that the threshold of sensation is very close to the threshold of audibility at the frequencies used. The power output necessary to reach the sensation threshold was only 3 db lower than the power needed for audibility.

The control of reverberation has been successfully undertaken in motion pictures and radio. The devices involved have included the echo chamber, vibrational transmission along springs and various means of recording and near-instantaneous playback. The problem in legitimate production is complicated by several conditions not encountered in radio or motion pictures: First, the legitimate theater or opera house usually has longer reverberation at most frequencies than the average motion picture theater or the room in which the radio receiver is located; second, the difference between the sound intensity of the show and the background audience noise level is generally less than in the case of motion pictures; third, the audience at a legitimate or operatic production conventionally demands much greater subtlety and flexibility in the auditory component of the show than is demanded of any other medium.

Devices for control of reverberation in the legitimate theater and opera must, therefore, possess ultimate flexibility. They must be able to reproduce reverberant conditions, including echoes, found in structures and in nature within the acoustic limitations of the theater, and must be susceptible of producing arbitrary, suggestive, or exaggerated phenomena in conformity with artistic demands which do not necessarily involve imitating nature.

The episodes employed to study the theatrical use of reverberation control were Widor's "Toccata in *F*," to which we added reverberation to an extent which would approximate that at the Church of St. Sulpice. The experiment was welcomed with considerable enthusiasm by all but a very few members of the audience, which included a number of eminent musicians. One who had heard the "Toccata" played in St. Sulpice declared that we had reproduced exactly the acoustical conditions obtaining there. I doubt that we did as well as that. I attribute the audience enthusiasm to (1) the fact that the "Toccata in *F*" is of itself a most effective showpiece, and that it was staged for a maximum effectiveness within the limitations of the theater, (2) the excellent performance of the organist, and (3) the fact that the piece was played at peaks at a level high enough to make almost anything exciting.

Reverberation was accomplished by recording on steel tape by the device to be described by S. K. Wolf. The reverberation machine was so arranged that the first playback occurred $\frac{1}{8}$ of a second after recording of the original sound, and 3 seconds passed before the last playback dropped below audibility. The first playback was 6 db below original level; the last started 15 db below. There were 9 intermediate pick-ups, adjusted in point of time to conform to acoustic conditions of the theater. The first playback had to be delayed to avoid feedback until the level of the normal reverberant sound in the theater had dropped 6 db.

The "Toccata" was originally played on the Paramount Theater studio organ, recorded on a vertically cut disk, and played back over 52 speakers located in the house and stage. The reverberation playback was through a separate set of speakers to contrast in direction to the original sound. The quality of the recording was sufficient to deceive the audience into believing that a real organ was present in the theater. The fact that the piece as played had almost no pauses made it difficult to perceive the dying away of single notes. Applause followed the final chord so soon that its reverberation was never perceptible for more than the first second. The "Toccata in *F*" is a brilliant piece and it may be argued that reverberation

can be much more effectively added to some of the compositions of Bach.

The same apparatus was employed in the church scene from "Faust" in which Margarita's efforts to pray are stifled by the presence of the voice of Mephistopheles. In this scene, the song of Margarita coming directly from the singer, the voice of Mephistopheles coming from speakers located in various places at various times, the organ accompaniment coming from speakers backstage, and the orchestral accompaniment, were picked up and played back via the reverberation apparatus. The added brilliance and churchlike quality were particularly noticeable in the first five measures of Margarita's song, which is unaccompanied.

The experiment with "Faust" was so successful as to make us confident that the technique involved can be employed to good advantage in opera in that it serves to establish locale, create mood, and generally carry out the intention of the composer more faithfully than any other means so far attempted.

In conclusion, our observations indicate that: (1) the remade voice is most effective if the intelligence it is to convey is supplemented or reinforced by the nature of the modulated sound and by some visual component of the play. (2) Subsonics have been proven effective, but in so special a case as to make generalizations with respect to them impossible. (3) Reverberation control is susceptible of immediate and wide use

Theory of Conical Sound Radiators*

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An expression is derived for the sound pressure resulting from the vibration of a conical sound radiator and the sound field is compared to that generated by a plane piston.

INTRODUCTION

THE case of a rigid plane piston vibrating in the surface of an infinite plane baffle has been treated in the literature.[1] However, most sound radiators occurring in practice are conical in shape and are rigid only at comparatively low frequencies. In attempting to develop a more exact theoretical treatment of the direct radiating loudspeaker diaphragm an expression has been derived for the sound pressure due to a rigid conical piston vibrating in an infinite plane baffle. Provision has been made also for taking into account the effect of nonrigidity which is axially symmetrical.

RIGID CONE

In Fig. 1 dA is the element of area on the conical surface with vertex at O and vertex angle 2α. P is the point at which the sound pressure is to be calculated. The distance from P to the origin is represented by r, the distance from P to dA by h, and the distance from dA to the origin by s.

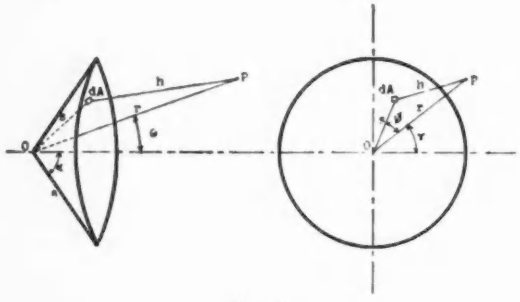

FIG. 1.

It can be shown that for the spherical coordinate system indicated,

$$h-r=-s(\cos\theta\cos\alpha+\sin\theta\sin\alpha\cos\phi). \qquad r\gg s \quad (1)$$

$$dA=sd\phi ds\sin\alpha. \quad (2)$$

The element of pressure at P is given by (3).

$$dp=i\frac{\rho\nu u\sin\alpha}{r}\exp\left[i\frac{2\pi(r-ct)}{\lambda}\right]\times\exp\left[-i\frac{2\pi s\cos\theta\cos\alpha}{\lambda}\right]\times\exp\left[-i\frac{2\pi s\sin\theta\sin\alpha\cos\phi}{\lambda}\right]sdsd\phi. \quad (3)$$

u = axial velocity of cone at driving point; ν = frequency in c.p.s.; ρ = density of air; c = sound propagation velocity in air; $\lambda=c/\nu$.

The resultant pressure at P is given by (4).

$$p=i\frac{2\pi\rho\nu u\sin\alpha}{r}\exp\left[i\frac{2\pi(r-ct)}{\lambda}\right]\times\int_0^a\exp\left[-i\frac{2\pi s\cos\theta\cos\alpha}{\lambda}\right]\times J_0\left(\frac{2\pi s\sin\theta\sin\alpha}{\lambda}\right)sds. \quad (4)$$

Equation (4) has been derived only for points P inside the extended cone; that is $\theta\leqslant\alpha$. Equation (4) can be integrated with a differential analyzer or by Simpson's rule for different values of a/λ, θ and α. It is not possible to express the characteristics of the conical piston in a single general curve. It will be evident that for each value of the cone angle α, a family of radiation patterns drawn for different values of a/λ is

* The material for this paper has been adapted from a thesis submitted by the writer in partial fulfillment of the requirements for the degrees of Master of Science and Bachelor of Science from the Massachusetts Institute of Technology.

[1] P. M. Morse, *Vibration and Sound* (McGraw-Hill Book Company, Inc., New York, 1936).

required to express completely the properties of the rigid conical radiator.

Figure 2 shows the result of integrating (4) with different values of θ for a rigid conical diaphragm, $a=9$ cm, $\alpha=60°$, and $\nu=5000$. Also shown is the corresponding curve for a rigid plane piston of the same projected area and velocity. In Fig. 3 are shown calculated pressure phase angle curves for conical and plane pistons.

Inspection and comparison of the final integration processes in the plane and conical piston analyses lead to interesting conclusions. In both cases the resultant pressure at P is found by determining the resultant element of pressure due to the motion of each ring-like element of area on the diaphragm in the first integration and then summing up the pressures due to the different rings in the final integration. The first integration process is the same for the two cases. The second integration process is different for the two cases because of the exponential term, $\exp[-i(2\pi s \cos\theta \cos\alpha)/\lambda]$, which appears only in the conical piston integral.

In the plane piston case, the pressure vectors

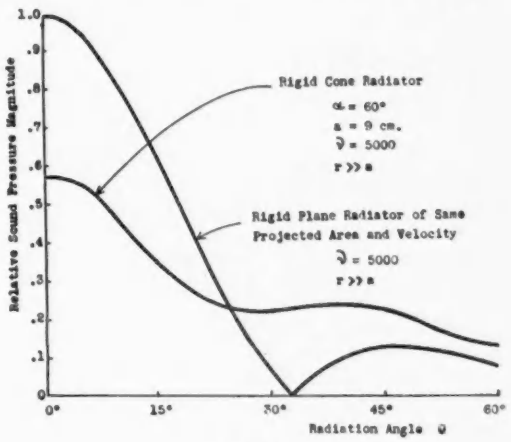

FIG. 2.

summed up in the final integration have only one degree of freedom. The J_0 function is positive for small values of the argument, passes through zero to negative values when the argument reaches 2.4, and continues much like a periodic function of rapidly decreasing amplitude. Starting at the center of the plane piston, the pressure vectors are positive until $2\pi s \sin\theta/\lambda$ goes to 2.4, when the vectors pass through zero and become negative. If $2\pi s \sin\theta/\lambda$ reaches 3.8, the sum of the pressure vectors is zero and there is a pressure node. A series of rapidly decreasing maxima separated by nodes follows as $2\pi s \sin\theta/\lambda$ continues to increase.

However, in the conical piston case, the vectors have two degrees of freedom because of the exponential term and do not, in general, cancel out to leave pressure nodes. Generally speaking, the pattern for a conical radiator of dimensions comparable to λ does not resemble that for a

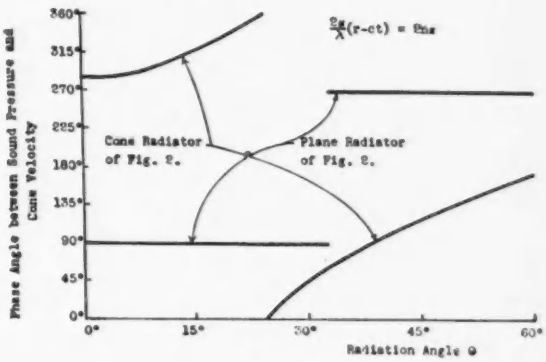

FIG. 3.

plane piston radiator of the same projected area, except that in both cases the magnitude of the sound pressure tends to drop off as $2\pi s \sin\theta/\lambda$ increases.

An additional point of difference brought to light by the analysis is illustrated in Fig. 3. In the case of the plane piston, the phase of the sound pressure at a constant distance from the center of the piston is, except for sign changes, independent of θ. In the case of the rigid cone, the phase of the sound pressure at a constant distance from the vertex of the cone varies with θ except for very small values of θ.

NONRIGID CONE

The modes of vibration of a loudspeaker cone are quite complex at high frequencies. Consider the hypothetical case of a circular transverse wave front traveling outward with a velocity uniform along the radius of the cone. If the wave front encounters the cone's characteristic impedance upon reaching the periphery, the wave is not reflected. In this special case the amplitude of vibration is essentially constant along the radius and there is a phase lag along the radius

because of the radial velocity of sound propagation in the diaphragm material.

This idealized case is seldom encountered in practice but is of theoretical interest. Letting c_d represent the radial velocity of sound propagation in the diaphragm, and allowing for the resulting phase lag along the radius of the diaphragm, the integral of (4) becomes

$$\int_0^a \exp\left[-i\left(\frac{2\pi s\cos\theta\cos\alpha}{\lambda}+\frac{2\pi cs}{\lambda c_d}\right)\right] \times J_0\left(\frac{2\pi s\sin\theta\sin\alpha}{\lambda}\right)sds. \quad (5)$$

Equation (5) is an expression for the diaphragm condition described and can be evaluated just as the integral for the rigid cone.

A second idealized case is that of radial sound propagation with complete peripheral reflection. In this case a standing wave pattern is set up and there are nodal rings on opposite sides of which the diaphragm motion is in opposite directions. This condition is more closely approximated in practice than the first condition.

A third idealized case is characterized by radial nodes. In the case of four radial nodes the cone's projected area appears to change from an ellipse in one half of the cycle to the same ellipse rotated 90° in the next half of the cycle. Radial nodes extend from the vertex of the cone to the four points common to the two ellipses. As many as 16 radial nodes have been observed.

At the very high audible frequencies the attenuation of sound along the radius is very great because of the mechanical properties of the cone material. At 10,000 c.p.s., radial attenuations of the order of 20 decibels per inch have been observed by the writer in commercial loudspeaker diaphragms.

There are also a large variety of effects caused by imperfect symmetry and homogeneity of the diaphragm. A typical source of asymmetry is the radial seam to be found in many loudspeaker diaphragms. At any one frequency it is likely that most of the five conditions described have some part in determining the motion of the diaphragm. Moreover, the relative importance of all but attenuation changes rapidly with frequency.

It is also interesting to note that there is both longitudinal and transverse wave motion in an axially driven conical diaphragm. The effect of compressional waves on the acoustical output of commercial cones is unknown. If the amplitude of the longitudinal or compressional wave is very small in comparison to the amplitude of the transverse wave the effect of the compressional wave is negligible.

Provided that the mode of vibration of the diaphragm can be either calculated or determined experimentally, (4) can be modified to take any axially symmetrical nonrigidity into account. The mode of vibration of the diaphragm can be examined experimentally by the method of Strutt.[2] If symmetry is observed and if the magnitude and phase of the axial velocity is measured along the radius and represented by $uf(s)$, the integral of (4) becomes

$$\int_0^a f(s)\exp\left[-i\frac{2\pi s\cos\theta\cos\alpha}{\lambda}\right] \times J_0\left(\frac{2\pi s\sin\theta\sin\alpha}{\lambda}\right)sds. \quad (6)$$

The foregoing has indicated the significant differences between conical and plane radiators, and offers a usable if laborious method for calculating the field generated by any axially symmetrical conical sound radiator. The writer feels that the theoretical approach to the study of direct radiating loudspeakers has been unduly neglected, and hopes that the present work will eventually lead the way to a more practicable analysis.

Acknowledgment

The writer takes this opportunity to thank Professor R. D. Fay, who supervised the thesis project and offered timely suggestions and encouragement in the preparation of the paper.

[2] M. J. O. Strutt, "On the amplitude of loud speaker cones," Proc. I. R. E., May (1931).

Heat Conduction Effects in Sound Emission

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(Received May 14, 1941)

This paper presents the mathematical formulation of the heat conduction phenomena occurring at the surface of a sound emitter, wherein the medium considered to be receiving the sound and impeding the motions of the source is a gas. The method employed is that previously used by Herzfeld to discuss reflection. The result is that due to the rapid, approximately adiabatic, compressions and rarefactions, an alternating temperature gradient and therefore temperature wave, is set up in the solid source and in the medium in such a manner as to cause a reduction in the total amount of sound energy radiated from the source. This effect is expressed in terms of two out-of-phase components of particle velocity amplitude. One is of the regular sound propagation, while one is a weak, slow, highly damped wave. The ratio of the regular wave amplitude to that of the source represents a complex coefficient of emission. This emission coefficient is compared with the reflection coefficient, and the losses are found to be just half as great as in the latter case. Such a complex emission coefficient implies the same form for the effective impedance of the medium on the source, i.e., the ratio of pressure to velocity, and accordingly this radiation impedance is partially reactive and partially resistive; each of these parts is given its explicit expression in terms of measurable physical characteristics of the medium. The results had previously been applied in the revision of Hubbard's theory of the ultrasonic interferometer to take account of these heat conduction effects, and the experimental verification of the predicted reflection coefficients for several gases is taken as experimental justification of the theoretical synthesis given.

INTRODUCTION

HEAT conduction as it affects the reflection of sound has been discussed[1] and the results applied[2,3] and compared with experiment. However, before the latter was possible, the theoretical discussion of these same effects as they occur at the source of sound emission was needed. The result of the latter discussion was used, in the application,[2] without giving the details of the synthesis. It is the purpose of the present discussion to show how the method used in the treatment of reflection[1] for reflection coefficients can be used for emission, and thereby obtain the corresponding expression for the emission coefficient, i.e., the ratio of emitted to impressed velocity amplitudes; and secondly, to write from this first result the expression for the mechanical impedance offered the source by the medium. The results are, that the losses due to the emission coefficient are just half as great as those due to a single reflection, and that the mechanical impedance is made up of two parts, a small reactive one and the principal resistive one, in which the latter is smaller than the corresponding wholly resistive impedance obtained when these heat conduction effects are neglected.

In the discussion[1] of reflection as influenced by heat conduction, the following results were obtained: (a) a periodic temperature wave in the solid boundary was found for which the analytical expression was given in terms of the heat properties of the solid and the frequency of the alternations; (b) in the gas, wave systems of two velocities were found to exist, and the characteristic constants were given in terms of the thermal and elastic properties of the gas. The two wave systems were called "regular" and "temperature" waves; they were found to be out of phase with one another and the second was highly damped, and moved with an extremely slow velocity compared with the regular. Two effects are apparent: continual absorption due to heat conduction in the gas; and, what is more important, when the boundary conditions were applied, considerable loss in the amplitude of the regular reflected sound wave appeared. This loss was found to increase with the frequency of the sound waves and to depend upon the properties of the gas and solid. These same considerations control the case for emission, except that the boundary conditions are different, since there is no incoming wave. Instead, now, the velocity amplitude of the source must make

[1] K. F. Herzfeld, Phys. Rev. **55**, 899 (1938).
[2] R. S. Alleman, Phys. Rev. **55**, 87 (1939).
[3] J. C. Hubbard, Phys. Rev. **38**, 1011 (1931); **41**, 523 (1932).

up both the regular sound wave as well as the "temperature" sound wave. The two again will be out of phase, i.e., of different velocities, the latter highly damped, and consequently the resultant sound wave emitted is considerably diminished in intensity.

Emission Coefficient

In what follows the only change in notation from that used for reflection[1] will be $\nu=\omega/2\pi$ for the frequency of the sound waves. In each step where the two problems, reflection[1] and emission, are identical, only the final expressions of the needed results of the former will be stated, and the equations from that discussion will be given the same numbers except that they will be followed by the letter H.

One of the differential equations which express the relations between particle velocity, u, and temperature T' in the gas medium was

$$(\partial^2 u/\partial x^2)+(\omega^2 M/RT_0)u=(i\omega/T_0)(\partial T'/\partial x). \quad (4'\text{H})$$

This came from the equations of continuity and motion, and together with another, (5″H), from energy conservation and continuity, gave, after appropriate solution, the expressions for the two reciprocal wave-lengths, $\lambda_1/2\pi$ and $\lambda_2/2\pi$, respectively for the regular and "temperature" sound waves in the gas:

$$\lambda_1^2=-\omega^2/V^2 \quad \text{and} \quad \lambda_2^2=i\nu/\epsilon^2. \quad (8\text{H})$$

The temperature distribution in the solid was given as

$$T''-T_0 = F\exp\left[i\omega t+(1+i)(C''\pi\omega/K'')^{\frac{1}{2}}x\right], \quad (2\text{H})$$

and this when combined with the general boundary conditions of continuous heat flow, (12H), and possible temperature jump, (13H), yields

$$T'-T_0=(\partial T'/\partial x)\Gamma, \quad (1)$$

where Γ is placed as an abbreviation for

$$\frac{1}{k}+\frac{K'}{K''}\frac{1}{(1+i)}\left(\frac{K''2}{C''\omega}\right)^{\frac{1}{2}}.$$

Now the new solution for (4′H), for the present case of emission, is

$$u=B'\exp(-\lambda_1 x)+G'\exp(-\lambda_2 x), \quad (2)$$

where B' and G' are the velocity amplitudes due to the regular and "temperature" waves, which must be related to the velocity amplitude, u_0, of the source by

$$u_0=B'+G'. \quad (3)$$

If u is eliminated between (2) and (4′H), one has after integration and substitution of the abbreviation $\Lambda=\lambda^2(1+\omega^2 M/RT\lambda^2)$

$$T'-T_0=-\frac{T_0}{i\omega}[B'(\Lambda_1/\lambda_1)\exp(-\lambda_1 x) +G'(\Lambda_2/\lambda_2)\exp(-\lambda_2 x)]. \quad (4)$$

And now if the two expressions (1) and (3), for the boundary requirements, are used in (4) with $x=0$, one obtains the ratio of B' to u_0, the reflection coefficient, γ', as

$$\gamma'=B'/u_0=1+\Lambda_1(1/\lambda_1+\Gamma)\{\Lambda_2(1/\lambda_2+\Gamma) -\Lambda_1(1/\lambda_1+\Gamma)\}^{-1}. \quad (5)$$

The term Γ was shown[1] to be negligible for ordinary pressures and frequencies, and accordingly the emission coefficient becomes

$$\gamma'=1+\frac{\Lambda_1}{\lambda_1}\left\{\frac{\Lambda_2}{\lambda_2}-\frac{\Lambda_1}{\lambda_1}\right\}^{-1}. \quad (6)$$

To see the relation which the emission coefficient has to the reflection coefficient, one finds that (14H) can be written as

$$\gamma\equiv B/A=1+2\frac{\Lambda_1}{\lambda_1}\{\Lambda_2(1/\lambda_2)-\Lambda_1(1/\lambda_1)\}^{-1}, \quad (7)$$

if the term Γ is neglected. Thus (6) and (7) show that γ and γ' are simply related as follows:

$$\gamma'=\tfrac{1}{2}(1+\gamma) \quad (8)$$

—the result which was used[2] in modifying the interferometer theory to include heat conduction effects. Since the fractions by which γ and γ' differ from unity are very small, their exponential definitions, $\gamma\equiv\exp(-\beta-i\varphi)$, $\gamma'\equiv\exp(-\beta'-i\varphi')$, can be expanded and the following approximations can conveniently be used: $|\gamma'|=|\gamma|^{\frac{1}{2}}=1-\beta'$, $\beta=\varphi=2\beta'=2\varphi'$. The evaluation of $\gamma=B/A$ has been given,[1] (16H), so that the emission coefficient is completely determined by $\beta'=(\pi\epsilon/V)(R/C_v)(2\nu)^{\frac{1}{2}}$.

Radiation Impedance

In acoustical calculations one has need of the term radiation impedance, or the ratio of the pressure and velocity at the source, which for the case of purely elastic emission by a piston into an infinite medium is of a pure resistive nature expressed as

$$p_0/u_0=\rho V, \tag{9}$$

where ρ is the density of the medium and V is the velocity of propagation.

However, in view of the preceding discussion of dissipative losses, due to heat conduction phenomena, the acoustical impedance, $Z\equiv(p_0/u_0)\equiv\rho V_1(X+iY)$, has also a reactive term, Y, in the expression of pressure to velocity, as will be evident in what follows. Equation (2) states that a motion of the piston of amplitude u_0 produces a regular wave of amplitude B' and of velocity $V_1=\omega/\lambda_1$ and a temperature wave of amplitude G' and velocity $V_2=\omega/\lambda_2$. Each of these waves will produce a pressure on the source and the sum will be

$$p_0=\rho V_1B'+\rho V_2G'. \tag{10}$$

The amplitudes B' and G' are given in terms of u_0 and γ' by

$$B'=\gamma'u_0, \quad \text{and} \quad G'=u_0-B'=u_0(1-\gamma'). \tag{11}$$

Now, since $\gamma'=\exp[-\beta'(1+i)]\doteq 1-\beta'(1+i)$, the acoustical impedance for free emission is

$$\begin{aligned} Z\equiv p_0/u_0&=\rho V_1\gamma'+\rho V_2(1-\gamma')\\ &=\rho V_1[1-\beta'(1-V_2/V_1)]\\ &\quad -i\rho V_1[\beta'(1-V_2/V_1)]. \end{aligned} \tag{12}$$

Accordingly, the resistive and reactive coefficients, X and Y, respectively, of the impedance expression, are

$$\begin{aligned} X&=1-\beta',\\ Y&=-\beta' \end{aligned} \tag{13}$$

in which the term V_2/V_1 is neglected, since $V_2/V_1\doteq\beta'C_v/R$ is small compared with unity.

The Temperature and Frequency Effects on Ultrasonic Velocities in Carbon Dioxide

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Northwestern University, Evanston, Illinois

(Received May 16, 1941)

Ultrasonic velocity measurements in pure carbon dioxide gas were made at temperatures ranging from 25° to 530°C with frequencies from 27 to 147 kilocycles. Experimental variations published in earlier reports are traced to gas contamination and temperature gradient effects. Data are presented showing that the velocity is a function of both temperature and frequency. The velocity dependence on frequency becomes greater as the temperature is increased. This is due to an increased probability of the excitation of vibrational energy states as the temperature is raised. The results seem to show that the relaxation time for a transfer of energy from translational to vibrational states is longer than that for the transfer from translational to rotational states.

Introduction

CONSIDERABLE recent interest in the field of ultrasonics is evidenced by the many published papers, both theoretical and experimental. Some of the theoretical predictions have long remained unsubstantiated by accurate experimental work. In other cases conflicting theories have been supported by conflicting evidence. There is a need of more accurate experimental verification.

Theoretical considerations accept the fact that the velocity of ultrasonic compressional waves in certain polyatomic gases, notably carbon dioxide, should be a function not only of the temperature of the gas but also the frequency of the wave. Theories relating to this phenomenon involve a study of the energy states and energy transitions which take place in a gas molecule when subjected to ultrasonic energy.

An experimental study of the effect of temperature on the reduced velocity

$$(V_r = V_0[273/(273+t)]^{\frac{1}{2}})$$

of ultrasonic wave propagation in carbon dioxide was made by Penman[1] in 1935. The relationships he obtained are shown in the curves drawn on Fig. 1. These curves show a dip between two flat plateaus, the dip minimum representing a condition where the sound frequency resonated with the molecular heat vibrations. It supports a theory known as the resonance theory.

A second theory called the collision theory was developed by K. F. Herzfeld and F. O. Rice,[2] Kneser,[3] and others. This theory holds that the sound energy, converted into internal energy of the molecules in the propagation of sonic waves, will be totally recovered only if the gas runs through states of equilibrium. At ultrasonic frequencies the interchange of translational and vibrational or rotational energy of the gas molecules no longer keeps pace with the rapid oscillations of pressure. The gas then behaves as though its effective heat capacity were decreased. The effect on the velocity of sound of an increasing frequency thus is a plateau followed by a rise terminated by a second plateau.

Increasing the temperature of the gas at a given frequency increases the transition probability. Thus a similar curve would be expected for a velocity *vs.* temperature relationship. Plotting, however, reduced velocity *vs.* temperature would reverse the plateau order. G. W. Warner,[4] repeating Penman's work, obtained curves characterized by the forms also shown in Fig. 1. No interpretation was published, but such results evidently support the collision theory. It is doubtful, however, that the complete effect should be produced in such a small temperature range.

[1] H. L. Penman, "The effect of temperature on supersonic dispersion in gases," Proc. Phys. Soc. **47**, 543–549 (1935).

[2] H. F. Herzfeld and F. O. Rice, "Dispersion and absorption of high frequency sound waves," Phys. Rev. **31**, 691–696 (1928).

[3] H. O. Kneser, "Zur Dispersiontheorie des Schalles," Ann. d. Physik, Leipzig, **11**, 761–801 (1931).

[4] G. W. Warner, "A study of the effect of frequency and temperature on the velocity of ultrasonic waves in gases," J. Acous. Soc. Am. **9**, 31–37 (1937).

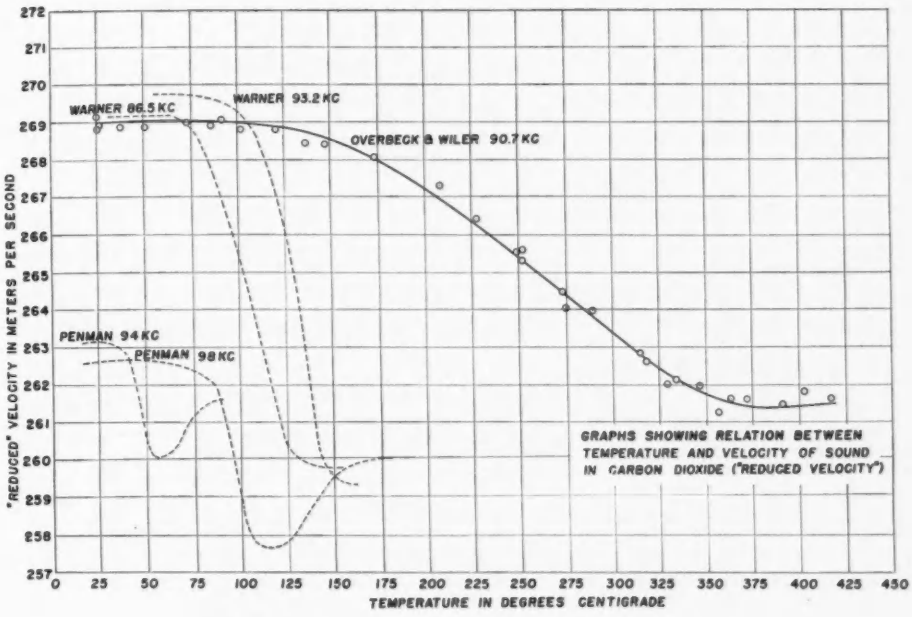

FIG. 1.

PRELIMINARY STUDY OF GAS CONTAMINATION

This experimental conflict concerning theories, which are important in fully understanding molecular behavior, led to a similar study by Overbeck and Wiler[5] in this laboratory. They attempted to find the reason for these experimental variations.

The result of the researches of Knudsen[6] and others concerning the effect of minute traces of impurities on the collision processes in CO_2, and an analysis of the experimental procedure used by Penman and Warner brought up the vital question of gas contamination as a possible explanation. An acoustic interferometer was built very similar to the apparatus used by them. Possible contamination sources—Bakelite, cork, rubber—were progressively removed from the interferometer. The investigation definitely showed that the presence of these materials at the temperatures used in the chamber released sufficient quantities of contaminating gas to produce a large variation in the results. The magnitude of the effect depended on the previous treatment of the gas-releasing material and the contamination increased rapidly with increasing temperature. Another possible very important source of contamination was the water vapor found in the tank CO_2. The velocity in CO_2 at 25°C for a 90-kc frequency wave was increased 9 meters per second by passing the tank gas slowly through a 90-cm P_2O_5 drying tube. Consistent readings resulted after a complete metal and glass gas chamber had been built and careful drying of the gas effected. Curve *C*, Fig. 1, resulted from this preliminary gas contamination study. The slope of the curve indicates a much slower transition probability change.

OTHER SOURCES OF ERROR

Recognizing that only one source of error had been carefully investigated in the preliminary study, and that the form of the high temperature end of the curve was not fully conclusive due to electrical losses and high absorption at these temperatures, the present authors decided to reconstruct completely the apparatus to enable the use of still higher temperatures, to increase the accuracy and to check other possible sources of error.

THE INTERFEROMETER

The interferometer mechanism and apparatus layout is shown in Fig. 2. The chamber wall was

[5] C. J. Overbeck and E. Wiler, "The effect of temperature on supersonic velocity in CO_2," Phys. Rev. **55**, 1127A (1939).

[6] V. O. Knudsen, "The absorption of sound," J. Acous. Soc. Am. **5**, 112–122 (1933).

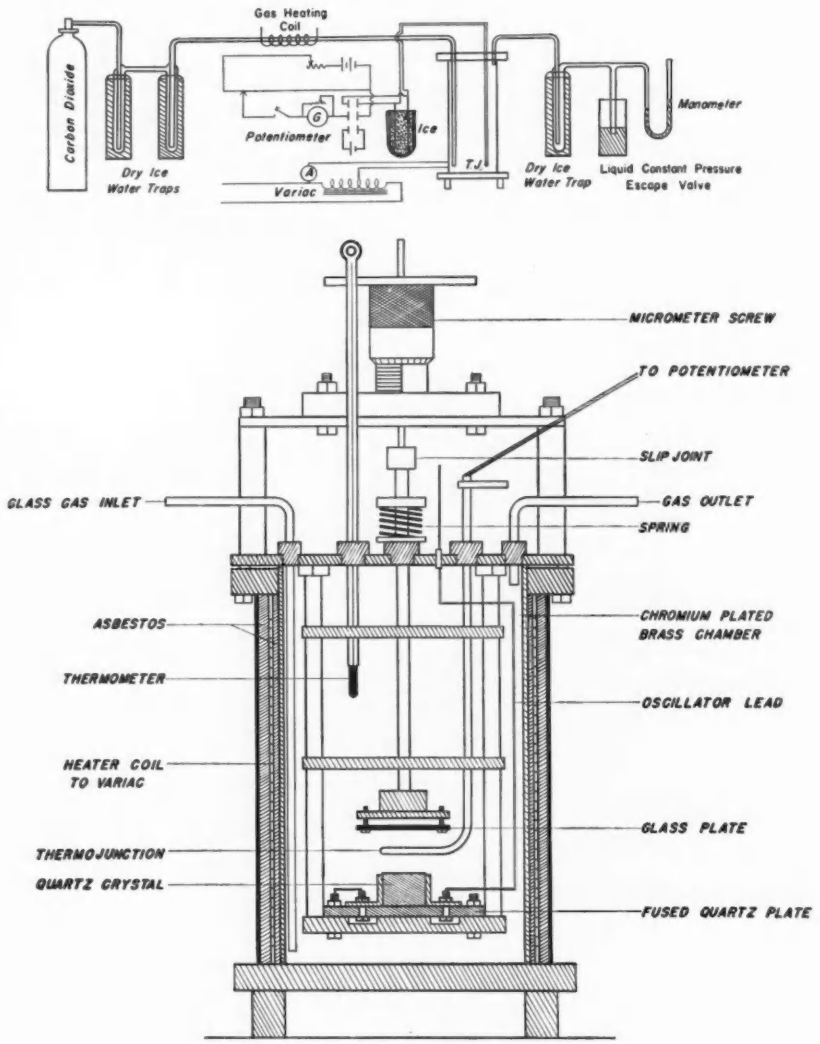

FIG. 2.

a section of brass tubing $\frac{1}{16}$ inch thick, 4 inches in diameter and 10 inches high. A heavy brass collar was welded to the top end as a support for the top plate. Nichrome heater coils were wound around the chamber, which was well heat insulated. The capacity of this heater was sufficient to raise the chamber temperature above 575°C, the breakdown temperature of the crystal.

The crystal support and the micrometer screw with its attached reflector were made a part of the upper plate in order that careful alignment of reflector and crystal could be made before the unit was placed in the chamber. The interior of the chamber and all metal parts used within the chamber were heavily chromium plated to prevent contamination at high temperature. The only other substances in the chamber were quartz and glass.

The crystal electrodes were mounted on a fused quartz plate to reduce the electrical leakage common to glass at temperatures above 400°C. A spark plug served to lead in the crystal frequency alternating current. It was thus possible to take readings limited only by the breakdown temperature of the crystal.

TEMPERATURE MEASUREMENT

Another suspected source of error was the presence of a temperature gradient in the chamber. As a check, therefore, a thermometer

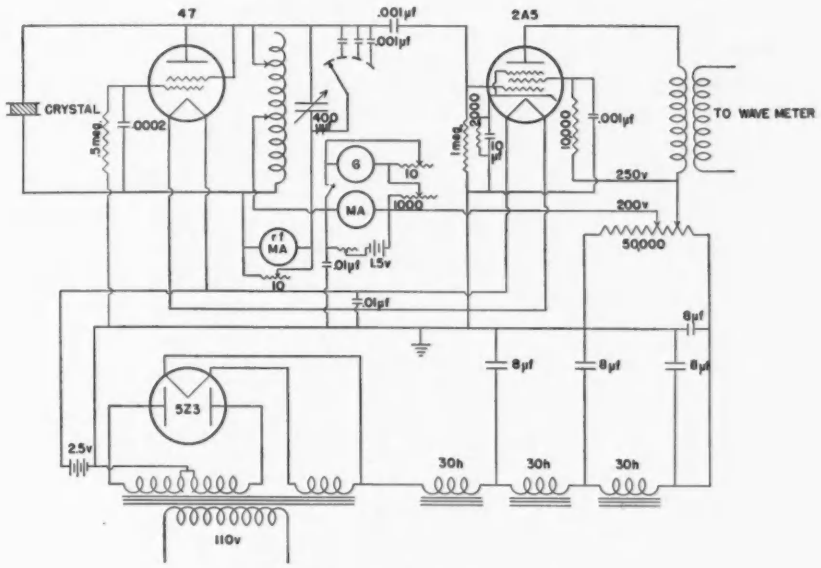

FIG. 3. Circuit diagram.

was placed in a position similar to its position in the preliminary study. A glass enclosed Chromel-Alumel thermocouple, designed to swing into the middle of the gas region between crystal and reflector, was used to obtain the gas temperature. This calibrated couple was connected to a Leeds and Northrup type K potentiometer. A temperature variation of a fraction of one degree could be detected by this method.

THE GAS AND DRIER

Two sources of carbon dioxide were used. The first source was a special high purity tank of carbon dioxide containing less than 0.04 percent foreign gases, composed largely of nitrogen and a trace of water vapor. The light foreign gases were, in part, removed by allowing the gas from a new tank to escape rapidly for a short time, thus blowing off the lighter gases collected at the top of the tank. Runs were also made using CO_2 gas sublimated from dry ice. The experimental results obtained from changing the source could not be differentiated. Chemical tests on the two sources indicated approximately the same high degree of purity.

The water vapor was removed by one of two methods. Initially the gas was allowed to pass slowly through a tube 90 cm long containing C.P. reagent P_2O_5. Later, to guarantee that disturbing foreign gases were not introduced by this drier, a set of dry ice freezing traps was substituted. Both methods appeared equally effective for a slow gas flow.

Before making any readings the carbon dioxide was allowed to flow through the system for a period of an hour or more, and on occasion even overnight. Slight leakage at the end of the chamber insured that no trapped air gases were pocketed. All readings were taken under a pressure excess of about one cm of water. To drive out possible water vapor from within the chamber, the interferometer was always heated to a high initial temperature. Readings were taken as the chamber cooled to stable temperatures determined by the current set for the heater coils.

THE OSCILLATOR AND CRYSTALS

The oscillator, whose circuit is shown in Fig. 3, employed a 47 tube operating as a triode coupled to a tuned *LC* circuit. The condenser feedback from tank coil to grid was very successful, and did away with the troublesome "tickler coil." The tank coil was wound of very low resistance wire to promote circuit sensitivity.

The piezoelectric crystals used in the work were cut and ground in this laboratory from a large natural quartz specimen. Five crystals were used ranging from about 27 kc to 150 kc.

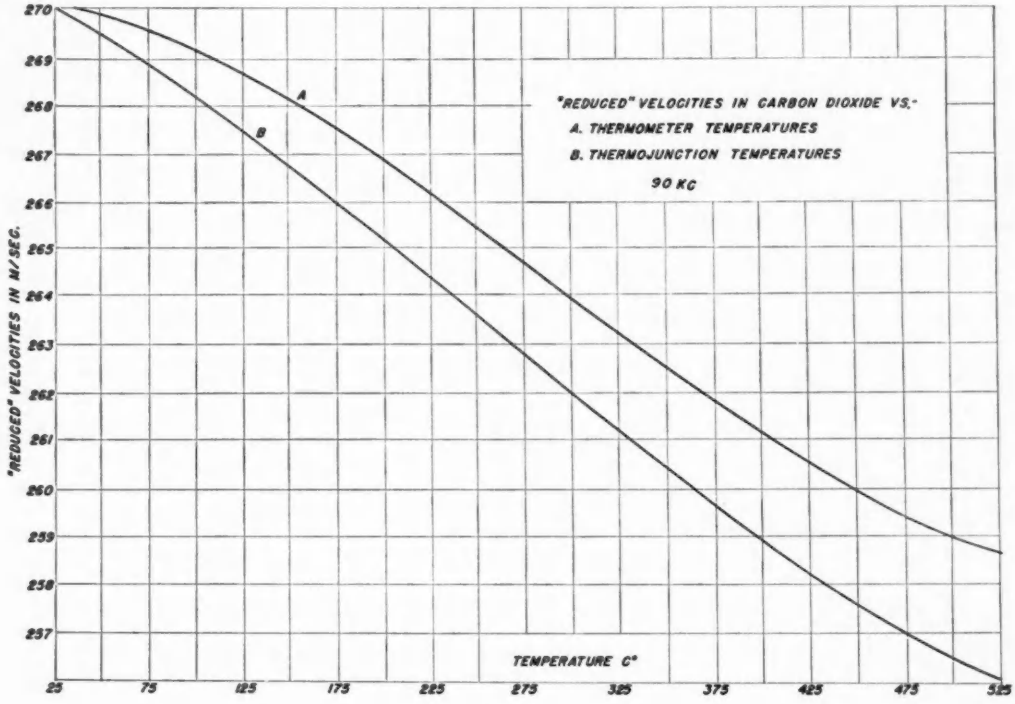

FIG. 4.

FREQUENCY MEASUREMENT

Since the crystals used in the sonic chamber had a marked temperature coefficient of frequency, an accurate determination of frequency had to be made at each new temperature. These frequency measurements were made using the beat method between known frequencies. A 100-kc crystal-controlled oscillator was calibrated using the signal of WWV as a standard. A precision variable oscillator having a frequency range from 100 kc to 300 kc was coupled to the crystal oscillator producing a beat note of from zero to 200 kc whose value was accurately known. This beat note, when coupled with the interferometer oscillator frequency, produced a second beat note. With proper adjustments of the variable oscillator, a resulting zero beat note between the interferometer oscillator and the frequency meter could be obtained. Thus the interferometer-crystal frequency could be accurately calculated. In all the measurements, the frequency was accurate to one part in ten thousand.

EXPERIMENTAL PROCEDURE

After taking the precautions to prevent contamination, mentioned in the preceding sections, the chamber was permitted to stand with a very slow gas flow and a predetermined heater current until temperature equilibrium was attained. The reflector plate was then lowered and a nodal point near the crystal face located. Repeated readings were made of the micrometer settings for a mean value of this nodal point position. Variations in the individual readings rarely exceeded a few hundredths of a millimeter.

The reflector was then raised and a rapid reading made of successive nodal points to check the half-wave-lengths covered in the standing wave system. The last nodal point was again repeatedly read and the mean of from ten to twenty settings was used. Gas absorption for this longer path did not permit quite as precise a resetting as was common to the first nodal point.

Immediately following this reading the thermojunction was swung into the middle of the standing wave gas space and an equilibrium temperature reading recorded. The crystal frequency was also measured at the same time. From these data the velocity value was computed and plotted.

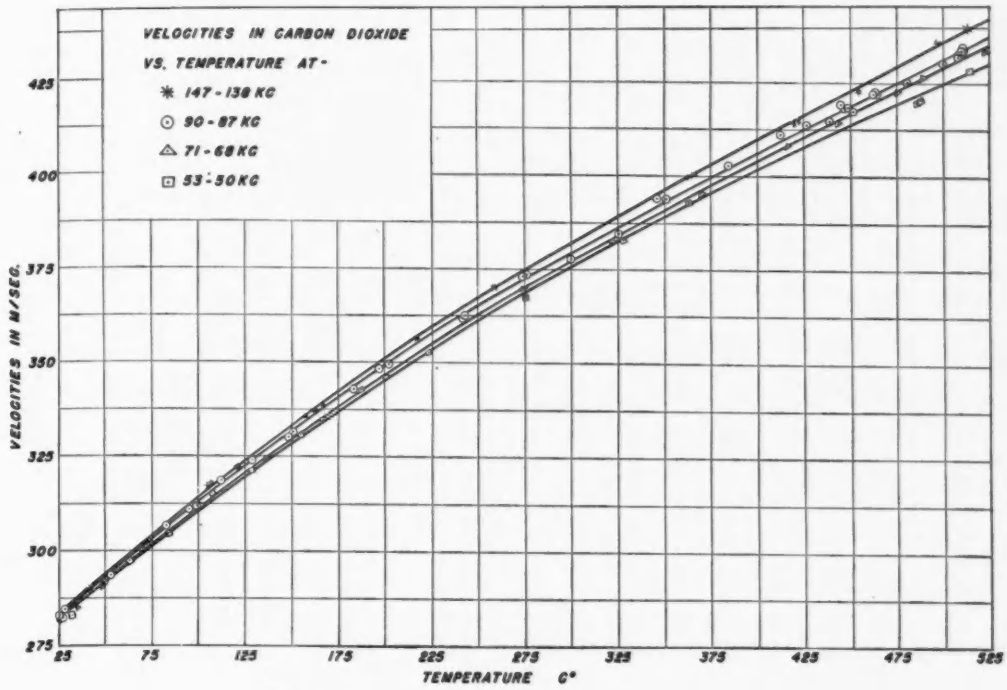

FIG. 5.

TEMPERATURE GRADIENT EFFECT

In Fig. 4, curve *B* shows the variation of reduced velocity with temperature using thermojunction temperatures. Curve *A* is drawn using corresponding thermometer readings. The variation is due to the temperature gradient within the chamber. It was surprising to note that, even when the incoming gas was carefully heated before being introduced into the chamber, a large temperature gradient existed between the active gas space and the position of the thermometer. Readings taken by shifting the position of the thermocouple between these two points checked the measured gradient. The strong initial plateau obtained in the preliminary work was evidently due to incorrect temperature readings. The authors thus conclude that temperature gradients in the chambers account for the balance of the discrepancies in the earlier reports.

The reduced velocity at room temperature, as measured on the present, more sensitive, apparatus, is one meter per second greater than found in the preliminary work. Calculations show a temperature uncertainty of about two degrees will account for this variation at 25°C.

EXPERIMENTAL RESULTS AND CONCLUSIONS

The curves of Fig. 5, plotting actual velocity of the ultrasonic compressional waves against the temperature of the carbon dioxide gas, show that the velocity is a function of both temperature and frequency. The spread of individual readings may be deduced from this figure. Attempts were made to obtain velocity values with a 27-kc crystal. Experimental difficulties, higher energy absorption, and crystal instability made these results less reliable than the ones plotted, but the points fall below the curves of Fig. 5. Table I is a set of representative values of the velocities read from the large original curves.

At room temperature and 147 kc the velocity is one and a half meters per second greater than the velocity of the wave set up by the 53-kc crystal. This agrees very closely with the findings of Pierce.[7] The spread increases to about 11 meters/sec. at 500°C for approximately a 100-kc range. The increased spread with temperature shows an increased probability of the excitation of vibrational energy states which are

[7] G. W. Pierce, "Piezoelectric oscillators applied to the precision measurement of sound in air and in carbon-dioxide at high frequencies," Proc. Am. Acad. Boston **60**, 269 (1925).

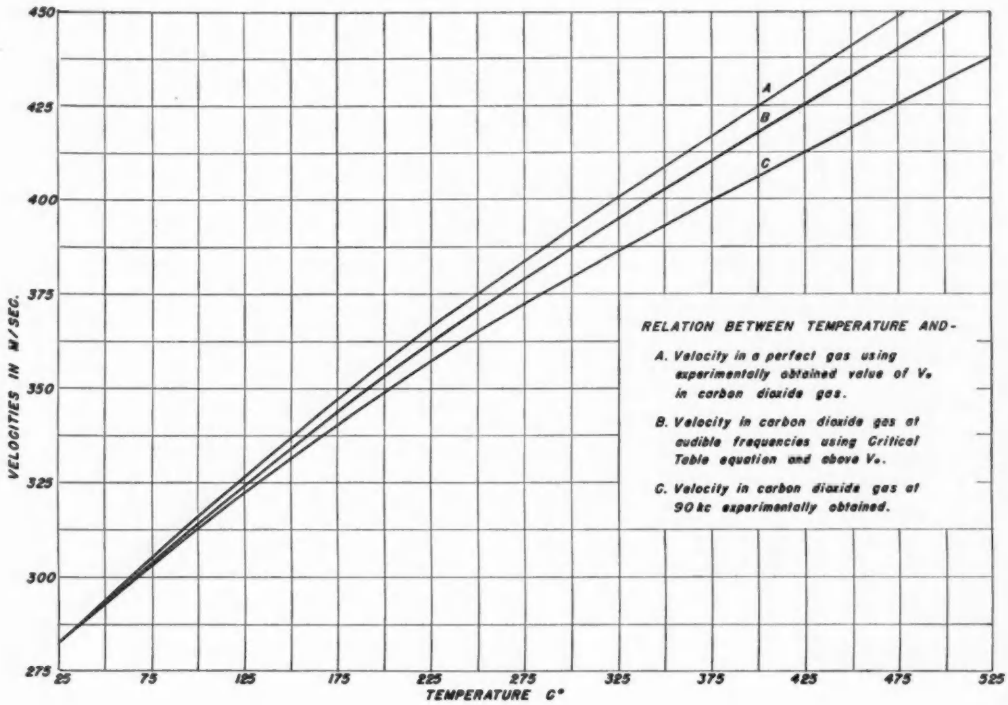
VELOCITIES IN M/SEC.
TEMPERATURE C°
RELATION BETWEEN TEMPERATURE AND-
A. Velocity in a perfect gas using experimentally obtained value of V_o in carbon dioxide gas.
B. Velocity in carbon dioxide gas at audible frequencies using Critical Table equation and above V_o.
C. Velocity in carbon dioxide gas at 90 kc experimentally obtained.

FIG. 6.

TABLE I. *Velocity of ultrasonic waves in pure carbon dioxide gas.*

TEMP.	53 KC	71 KC	90 KC	147 KC
25°C	282.0 m/sec.	282.6 m/sec.	282.9 m/sec.	283.5 m/sec.
50°	291.0	292.4	293.1	293.5
100°	310.7	311.7	313.0	314.6
150°	328.4	329.2	331.0	333.1
200°	345.4	346.7	349.0	351.1
250°	361.1	362.4	365.0	367.5
300°	375.3	376.8	379.6	382.5
350°	388.9	390.4	393.4	396.8
400°	401.4	403.5	406.4	410.0
450°	413.6	416.4	419.1	423.1
500°	425.0	428.8	431.4	435.8
525°	430.6	435.0	437.9	442.1

not active at room temperature. The results seem to show that the relaxation time for a transfer of energy from translational to vibrational states is longer than that required for the transfer from translational to rotational states. The linear carbon dioxide molecule has its two equal rotational degrees of freedom fully excited at room temperature. However, the three natural frequencies of oscillation have only slightly contributed, or have not yet started to contribute, to the specific heat at this temperature.

Since the curves continue to diverge throughout the temperature range investigated, it is evident that complete contribution of all energy states to the molecular heat capacity has not yet been effected.

Curve *A* of Fig. 6 was calculated to show the relation between temperature and velocity, assuming carbon dioxide to be a perfect gas. Curve *B* was calculated using the equation appearing in the International Critical Table for the velocity in carbon dioxide at audible frequencies

$$V=271[1+(3.53t\cdot 10^{-3})-(0.21t^2\cdot 10^{-6})]^{\frac{1}{2}}.$$

Curve *C*, transferred from Fig. 5, shows our experimentally obtained velocity values at 90 kc.

If we are to accept the curves in Fig. 5 which show a rise in velocity with rise in frequency, at a given temperature, curve *B* should diverge below curve *C*. Such behavior would also follow from theoretical considerations.

In conclusion the authors wish to express their indebtedness to Mr. E. Wiler for his contribution toward the completion of this investigation. Our thanks are due also to members of the Physics Department for helpful criticism.

The Origin of the Absorption of Ultrasonic Waves in Liquids

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(Received June 4, 1941)

It seems now experimentally certain that the absorption of sound waves in water, benzene, carbon tetrachloride and methyl alcohol is strictly proportional to the square of the frequency up to 50 megacycles, but considerably larger than can be explained by viscosity and heat conduction. It is shown here that an explanation of this increased absorption by slowness of energy exchange between internal and external degrees of freedom is not in disagreement with the facts for the three last named liquids, while the absorption in water must have a different origin.

SEVERAL measurements of the absorption coefficient α for ultrasonic waves of high frequency in polyatomic liquids have recently been published.[1,2] These show α proportional to ν^2, but higher than can be explained by viscosity and heat conduction alone. That α is proportional to ν^2 shows that the period of the sound wave is still much longer than the characteristic relaxation time.

If one assumes that the increased absorption in liquids is due, just as in gases, to the slowness of exchange between external and internal energy of the molecule, one can get an upper limit of this time from the specific heat of the internal vibrations of the molecule. We have to make the assumption that the specific heat of the internal vibrations of the molecule is the same in the gaseous and in the liquid state for the same temperature.

If we call this value C' it can be found from the specific heat of the gas, measured quasi-statically, through

$$C' = C_{p\,\mathrm{gas}} - \frac{7}{2}(\text{or } 4)R, \tag{1}$$

$7/2R$ to be used for linear molecules, $4R$ for non-linear ones.

For high frequencies,[3] C' has to be replaced by

$$C'/1+i\omega\vartheta,$$

where ω is $2\pi\nu$, and ϑ is a relaxation time characteristic for the energy exchange. The equation of the propagation of sound is then

$$\frac{V_0^2}{V^2}\left(1-i\frac{\alpha' V}{\omega}\right)^2 = \frac{C_v}{C_p}\frac{C_{p0}}{C_{v0}}, \tag{2}$$

where V is the velocity of sound at frequency ν, the index zero refers to frequency zero, and α is the absorption coefficient of the amplitude, so that the intensity falls by the factor e^{-1} over a distance $(2\alpha)^{-1}$. α' is the part of α that is not due to viscosity.

If we write

$$C_{v0} = C + C'$$

C_v will be

$$C_v = C + C'/(1+i\omega\vartheta). \tag{3}$$

Furthermore, we write

$$\Delta = C_p - C_v$$

and omit from now on the index 0 on C_p, so that this letter signifies the "molal specific heat," measured in the usual caloric way. Then

$$\frac{V_0^2}{V^2}\left(1-\frac{i\alpha' V}{\omega}\right)^2 = \frac{C_p-\Delta-C'+\dfrac{C'}{1+i\omega\vartheta}}{C_p-C'+\dfrac{C'}{1+i\omega\vartheta}}\frac{C_p}{C_p-\Delta}$$

$$= 1-\frac{\Delta C'}{C_p-\Delta}\frac{(C_p-C')\omega^2\vartheta^2}{C_p^2+(C_p-C')^2\omega^2\vartheta^2}$$

$$-\frac{C'\Delta}{C_p^2+(C_p-C')^2\omega^2\vartheta^2}\frac{C_p}{C_p-\Delta}i\omega\vartheta. \tag{4}$$

[1] G. D. Rock and F. E. Fox. J. Acous. Soc. Am. **12**, 505 (1941).
[2] A. Lindberg, Physik. Zeits. **41**, 457 (1940).
[3] W. T. Richards, Rev. Mod. Phys. **11**, 36 (1939); also, H. O. Kneser, Physik. Zeits. **39**, 800 (1938).

TABLE I. *Thermodynamic data (all except ϵ in cal./mole)*

LIQUID	C_p GAS	C'	C_p LIQUID	Δ[1]	ϵ (PURE NUMBER)
H_2O		0.152[2]	18	0.11	5×10^{-5}
C_6H_6	21.7[3]	13.8	32.1[4]	10.2	0.2
CCl_4	20.7[5]	12.8	31[6]	10	0.2
CH_3OH	11.8(77°)[7]	3.8	19.2[6]	3.9	0.05

[1] F. A. Schulze, Physik. Zeits. **26**, 153 (1925). A rough linear interpolation to 20°C has been made here.
[2] Calculated from the data of E. F. Barker and W. W. Sleator, J. Chem. Phys. **3**, 660 (1935).
[3] G. Déjardin, Ann. de physique **11**, 253 (1919).
[4] J. S. Burlew, J. Am. Chem. Soc. **62**, 696 (1940).
[5] Mills and McRae, J. Phys. Chem. **14**, 797 (1910).
[6] *Int. Crit. Tables*, Vol. 5, p. 107ff.
[7] *Int. Crit. Tables*, Vol. 5, p. 81. On the other hand, the data given by Th. de Vries and B. T. Collins, J. Am. Chem. Soc. **63**, 1343 (1941) correspond to C_p gas 19, $C'=11$, $\Delta=4.9$, $\epsilon=0.2$. The value for CH_3OH in Table II becomes then 1.36, in Table III $\vartheta=4\cdot10^{-12}$ sec., in Table IV $\nu=20{,}000$.

It follows then that

$$\left(\frac{2\alpha' V}{\omega}\right)_{\omega=0}=\frac{C'\Delta}{C_p(C_p-\Delta)}\omega\vartheta \tag{5}$$

or

$$\left(\frac{2\alpha'}{\nu^2}\right)_{\nu=0}=\frac{4\pi^2}{V_0}\frac{C'\Delta}{C_p(C_p-\Delta)}\vartheta. \tag{5'}$$

As long as α'/ν^2 is constant, it means that in (4) the quantity $(C_p-C')^2\omega^2\vartheta^2$ can be neglected next to C_p^2. We are going to abbreviate

$$C'\Delta/C_p(C_p-\Delta)=\epsilon$$

and calculate it from thermodynamic and, in some cases, spectroscopic data. The result is given in Table I. The least accurate value is C'. For water, C' calculated spectroscopically, is surely accurate to a few percent. For C_6H_6 and CCl_4 we might estimate the error at 10 percent, for CH_3OH C' might be wrong to a factor 2. Δ is probably accurate to at least 10 percent. Therefore, ϵ for H_2O is quite accurate, for C_6H_6 and CCl_4 to 20 percent and for methyl alcohol to a factor of 2. The maximum variation of the sound velocity is given by

$$\frac{V_\infty^2-V_0^2}{V_0^2}=\frac{C'\Delta}{C_p(C_p-\Delta-C')}=\epsilon\frac{C_p-\Delta}{C_p-\Delta-C'}. \tag{7'}$$

Equation (7) and Table II are, of course, not really applicable to infinite frequency but only apply if there exists a frequency which on the one hand is so high, that the internal vibrations cannot follow at all, while this frequency lies far below that of the thermal waves, which have a far different velocity of propagation.

With the values of ϵ contained in Table I, it is now possible to calculate from the experimental value of $2\alpha'/\nu^2$, as measured at relatively low frequency, the average relaxation time ϑ, according to (5'). (See Table III.)

$$\vartheta=\frac{V_0}{4\pi^2}\epsilon^{-1}\left(\frac{2\alpha'}{\nu^2}\right)_{\nu=0}. \tag{8}$$

We discuss first C_6H_6, CCl_4, CH_3OH. The small values of ϑ are in agreement with the fact that no drop in $2\alpha'/\nu^2$ has been observed up to 50 or 80 megacycles: At present, the measurements of α/ν^2 are still so inaccurate that not much less than a 10 percent variation could safely be asserted. For a 10 percent variation, $(C_p-C'/C_p)^2\omega^2\vartheta^2$ must be about 0.1. That is not quite exact, as we have neglected the variation in V. But with this accuracy then, this corresponds to $\omega\vartheta\sim\frac{1}{2}$ or $\nu\sim\frac{1}{12}\vartheta^{-1}$. Table IV gives the frequencies at which a 10 percent drop of $2\alpha'/\nu^2$ might be expected.

TABLE II. *Maximum dispersion.*

H_2O	C_6H_6	CCl_4	CH_3OH
$1+2.5\times10^{-6}$	1.24	1.23	1.025

All this is based on the assumption that all the internal specific heat C' has a uniform ϑ. Eucken and Kuechler[4] found that to be the case for gaseous CO_2. If it should not be so here, ϵ has to be replaced by $\Sigma\epsilon\vartheta$. In this case, it is possible that one or more internal degrees of freedom have a larger ϑ than the average value given in Table III and that a partial drop of α/ν^2 might appear at frequencies lower than those of Table IV. The compounds of Table IV have, however, so many internal vibrations that no more detailed study of the possibilities can profitably be made at present.

We turn now to the consideration of H_2O. The high value of ϑ found has nothing to do with the possibility of a region of dropping α/ν^2 near one megacycle, because the experimental value used for α/ν^2 applies to 10 to 80 megacycles. The value $\vartheta=2\cdot10^{-8}$ second means that an internal specific heat C' of 0.152 is too small to explain an

[4] A. Eucken and L. Kuechler, Physik. Zeits. **39**, 831 (1938).

absorption $2\alpha'/\nu^2 = 28 \cdot 10^{-17} (2\alpha/\nu^2 = 45 \cdot 10^{-17})$ in the region of 10 to 80 megacycles. If, in the region 10 to 80 megacycles, the quantity $(2\alpha/\nu^2)$ does not drop by 10 percent, it means that

$$\vartheta < 10^{-9} \text{ second}$$

and that means that the necessary C' would have to be more than 21 times bigger than 0.152 cal./mole or

$$C' > 3.2 \text{ cal./mole.}$$

This would mean that a large fraction of the "external" energy is only slowly exchanged against the rest. At 4°C, $C_p - C_v$ is zero for water. If an excess absorption should exist even then, this would show[5] that this excess absorption is not due to C_v but to the compressibility. According to Kneser,[6] Debye has expressed the opinion that the excess absorption might be due to the slowness of molecular rearrangement as dependent on pressure. In this case, one might formally try the equation

$$\frac{1}{\rho}\frac{\partial \rho}{\partial t} = -\frac{1}{\tau}\frac{\rho - \rho_0}{\rho} + \frac{\kappa}{\tau} \dot{p}. \tag{9}$$

It is true that it would be better to have the density change consist of two parts, one reacting quickly, one slowly, but (9) is a first approximation. From (9) one finds

$$\frac{V_0^2}{V^2}\left(1 - \frac{i\alpha' V}{\omega}\right)^2 = \frac{1}{1 + i\omega\tau}$$

and

$$(2\alpha'/\nu^2)_{\nu=0} = 4\pi^2\tau/V_0,$$

i.e.

$$\tau \sim 10^{-12}.$$

The dispersion would be given approximately as

$$V/V_0 = 1 + \tfrac{3}{2}\pi^2\nu^2\tau^2$$

and would be about $3 \cdot 10^{-8}$ at 50 megacycles, far beyond experimental accuracy.

TABLE III. *Relaxation time.*

LIQUID	H_2O	C_6H_6	CCL_4	CH_3OH		
V_0†	1.5	1.3	0.93	1.13	10^5	cm/sec.
$2\alpha'/\nu^2$	28[1]	1800[2]	900*	31[2]	10^{-17}	cm^{-1}
ϑ	2.1×10^{-8}	3×10^{-10}	1×10^{-10}	1.8×10^{-11}	sec.	

* H. Grobe, Physik. Zeits. **39**, 333 (1938).
† According to H. Bergmann, *Ultrasonics* (New York, 1938).

TABLE IV. *Frequencies at which a 10 percent drop in $2\alpha'/\nu^2$ might be expected.*

LIQUID	C_6H_6	CCl_4	CH_3OH
ν in megacycles	260	800	4400

[5] This was kindly suggested by Professor J. C. Hubbard. Experiments are planned in his laboratory.
[6] H. O. Kneser, Physik. Zeits. **39**, 800 (1938).

The Absorption of Ultrasonic Waves in Highly Viscous Liquids*

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(Received February 7, 1941)

The absorption of ultrasonic waves in glycerin, castor oil, linseed oil, and olive oil was studied at various temperatures and at two frequencies, 3.157 and 3.95 megacycles per second, respectively. These liquids were chosen because of their high viscosity and correspondingly high absorption coefficients. As the viscosity of the liquids used depends to a considerable degree on the temperatures, the experiment permitted the calculation of the temperature coefficient of absorption to a good measure of precision and the results thus obtained agreed within the experimental error with the theoretical values for the coefficient. The sonic resonator interferometer developed by Hubbard, and adapted by Fox for use with liquids in this laboratory, was used.

INTRODUCTION

THE absorption and dispersion of sound in gases is determined by three phenomena: viscosity, heat conduction, and slowness of energy interchange with internal degrees of freedom (relaxation time). The first two can be calculated theoretically, and therefore experiments have given valuable information concerning the energy exchange. It seems natural that the same questions should be investigated in liquids, although one should expect that because of the closeness of the molecules and the faster energy exchange because of this closeness, the absorption or dispersion depending on this slowness should occur at higher frequencies.

A number of direct absorption measurements in liquids have been undertaken but the results are very discordant among themselves. They have generally been much higher than one should expect from viscosity and heat conduction alone, and have been made at frequencies where an effect due to slowness of energy exchange would be very astonishing.

For example, Sorensen,[1] using a pressure balance method and very high ultrasonic intensities, found intensity absorption coefficients for many liquids of values several orders higher than would be expected on the basis of the Stokes-Kirchhoff theory. Biquard,[2] Claeys, Errera and Sack,[3] Wyss,[4] Bazulin[5] and many others, most of them using optical methods, have also found values much higher than the theoretical, and of great inconsistency from observer to observer, amounting in many cases to one or more orders of magnitude.

The first measurement giving an absorption for water comparable to the theoretical value was that of Fox,[6] who found a value of about twice the theoretical. The experimental difficulties are mainly due to the relative smallness of the values of absorption, and therefore it was thought useful to make measurements with liquids of high viscosity. These liquids should have high absorption which should be easier to determine. In addition, it so happens that the viscosity of the liquids used depends very much on the temperature. If, for example, the theory which has been used to evaluate the absorption coefficient from the rather complicated measurements should be wrong because of a wrong constant, one might at least get the right temperature coefficient of the absorption, if not the right absolute value.

The result of our measurements is that for glycerin, castor oil, linseed oil, and olive oil, the absolute value of the absorption coefficient agrees with the theoretical value within the rather large experimental error of 30 percent, although within this error the experimental values are consistently higher than the theoretical values

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† Now at John Carroll University, Cleveland, Ohio.

[1] C. Sorensen, Ann. d. Physik **26**, 120 (1936).

[2] P. Biquard, Thèse, Universitè de Paris (1935).

[3] J. Claeys, J. Errera and H. Sack, Comptes rendus **202**, 1493 (1936).

[4] R. Wyss, Helv. Phys. Acta **7**, 406 (1934).

[5] P. Bazulin, Physik. Zeits. Sowjetunion **8**, 591 (1935).

[6] F. E. Fox, Phys. Rev. **52**, 973 (1937).

expected from viscosity and heat conduction. In addition, the temperature dependence is the same for both theoretical and experimental values. The inaccuracy of the measurement makes it impossible to decide whether there is an additional absorption present which forms only a small part of the total absorption for liquids of high viscosity, and rather a large part for liquids of low viscosity. But theoretical considerations speak against this possibility.

The general method used here is that of the sonic interferometer developed by Hubbard,[7] and improved for use in liquids in this laboratory by Rock,[8] Quirk,[9] and Fox.[6] The essence of this method consists in measuring the reaction of the vibrating liquid column on the associated electrical circuit when the reflector is in a resonant position. If the length of the liquid column is varied, the measurements permit the calculation of the absorption coefficient. Incidentally, the sound velocities were also measured, although no trouble was taken to insure high accuracy.

The Theory of the Method

The acoustic interferometer, composed of a vibrator such as a piezoelectric plate which is electrically driven by an independent source, and to which is coupled a column of fluid set into longitudinal vibration by the plate, was first treated theoretically as an electromechanical system by Hubbard.[7] This theory was designed to apply to gases but was extended by Fox[6] to apply to liquids.

A circuit such as is shown in Fig. 1 represents the equivalent electrical circuit of the interferometer system and the associated pick-up system for driving it, by loose coupling of L_1 with an independent oscillator of constant frequency and amplitude. Here L_1, R_1, and C_1 are the inductance, resistance and capacity, respectively, of the pick-up circuit, K_1 is the electrode capacity of the quartz plate, and L, R' and K' are the equivalent series inductance, resistance and capacity of the quartz resonator with the coupled fluid column. The theory shows that R' and K' are modifications of R and K, the respective equivalent series resistance and capacity of the quartz plate at resonance without the coupled fluid column. These modifications vary in cycles and have a decrement as r is increased and can be followed by means of a thermogalvanometer in the L_1R_1 branch of the pick-up circuit. The value of current i so measured is made independent of the e.m.f. induced by the driving oscillator by dividing by I_0, the maximum

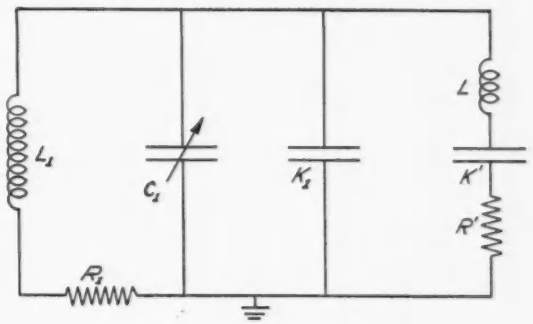

Fig. 1.

resonant current in the L_1R_1 branch when the quartz plate is clamped or replaced by a capacitance equivalent to K_1. Thus $\sigma = i/I_0$ is a function of r and also of α, the attenuation factor of particle velocity, and γ, the coefficient of reflection at the reflector of the interferometer.

The curves which show the cyclic change of the modifications of R and K with increasing r, and the measurement of such modifications by observation of σ have been thoroughly discussed by Fox[6] for the case of liquids. It is enough here to mention the significant characteristics, particularly of the $\sigma = i/I_0$ curve. First there is a sharp dip in the value of σ at critical points separated from each other by a distance of a half-wave-length. This permits calculation of the velocity. Secondly, there is a progressive rise in the height of the minimum values of σ, denoted by σ_m. This is due to the absorption coefficient. A further quantity of use in the theory is the constant

$$C = (1 - \sigma_0)/\sigma_0,$$

where σ_0 is the minimum value of σ in air, and C contains only constants of the system independent of the liquid.

[7] J. C. Hubbard, Phys. Rev. **41**, 523 (1932); **38**, 1011 (1931).
[8] A. L. Quirk and G. C. Rock, Rev. Sci. Inst. **6**, 6 (1935).
[9] A. L. Quirk, Doct. Diss., Catholic University of America (1934).

Experimental Procedure in Obtaining Absorption and Reflection Constants

A description of the apparatus is contained in Fox's paper. The interferometer consists of a cylinder which houses a quartz crystal in its base, and a reflector free to move upward and downward within this cylinder. The reflector is attached to the rod which supports it by a ball joint so that it may be pressed down upon the face of the crystal to insure parallelism. The

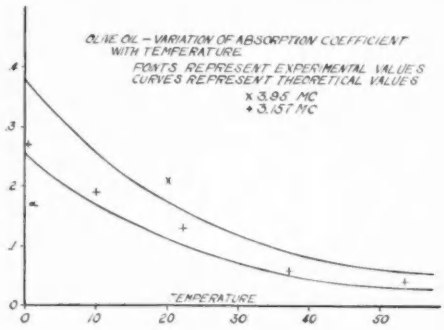

Fig. 2.

quartz crystal, as stated before, is connected in parallel with the condenser of an LC circuit, so that movement of the reflector, by affecting the pressure on the face of the quartz, affects the current in the LC circuit.

The crystal was cemented to the top of a disk of brass having a square opening slightly smaller than the quartz. The quartz was then sputtered with platinum; conduction being obtained in this way between the top of the crystal and the disk, and through the disk, to the ground. The high potential electrode is provided by a sputtered square of platinum on the bottom of the quartz which does not touch the brass disk. The value of C, i.e., $(1-\sigma_0)/\sigma_0$, is determined experimentally before each run.

The experimental procedure is as follows:

(1) The driving oscillator is loosely coupled to the quartz in the absence of the liquid, and tuned to the frequency of the crystal. This is indicated by a sharp dip in i, the current in the pick-up circuit.

(2) The crystal is disconnected from the driving circuit, and the pick-up circuit is tuned to resonance with the driving oscillator. This resonance is indicated by a peak value in i, which is called I_0.

(3) The liquid is placed in the interferometer and the joints are sealed with either picene or gum arabic. The interferometer is then placed in a thermostat controlled to 1/10°C, and the liquid in the interferometer is given time to come to temperature equilibrium.

(4) As the reflector is moved outwards, dips in the current appear. The reflector is stopped at the highest value of the current curve and the pick-up condenser readjusted to see if a higher value can be obtained. The highest value obtainable by adjustment of the pick-up condenser is the correct value.

(5) Attention is now paid to the actual shape of the first dip, for upon its shape depends γ, and indirectly, α. Accordingly, various values of σ near the minimum of the dip and the corresponding values of r are taken and plotted, these values giving a curve called the crevasse curve.

(6) The height of the minimum current at subsequent dips spaced at appropriate intervals is now taken. For instance, in castor oil at low temperatures a change in the value of the minimum current i_m, was noticeable at each consecutive dip, while in other liquids, and at higher temperatures, 10 dips could be taken before there was a noticeable change in the current value of the minimum.

It must be mentioned here that in the theory of the quartz resonator there is assumed a single response frequency; this was not found in practice. In all the crystals and at all the frequencies used in the investigation, satellite frequencies were present. The effect of satellite frequencies is to distort the shape of the crevasse curve.

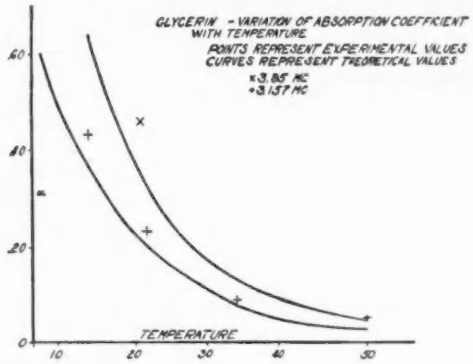

Fig. 3.

While in most cases it is possible to redraw the crevasse curve so as to eliminate the effect of the satellite frequency, the presence of these satellites introduces an unavoidable error into the experiment.

The absorption is calculated from the equation

$$r_i\alpha = C\frac{\sigma_{mi}}{S(1-\sigma_{mi})} - \frac{1}{S} + \frac{1}{2}\ln\gamma$$

which is derived in Fox's paper.[6]

Experimental Results

The greatest difficulty was met in trying to get an accurate idea of the reflection coefficient from the crevasse curve. After various attempts it was at length decided to concentrate on the side of the curve which was free of satellite dips and endeavor to calculate from the shape of this side where the minimum lay. Once the location of the minimum was established it was a relatively easy matter to calculate the reflection coefficient.

In doing this it is necessary to assume that the side of the crevasse which shows no dips is unaffected by the presence of satellite dips on the other side of the crevasse. Incidently, it is also assumed that there are no imperceptible

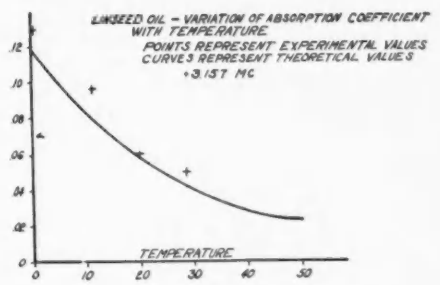
LINSEED OIL – VARIATION OF ABSORPTION COEFFICIENT WITH TEMPERATURE
POINTS REPRESENT EXPERIMENTAL VALUES
CURVES REPRESENT THEORETICAL VALUES
+3.157 MC
TEMPERATURE

Fig. 4.

satellite dips which might widen the crevasse without otherwise showing up. These assumptions seem safe enough, but it is difficult to estimate the error in the values of the absorption coefficient, as the absorption value depends upon the values found for S and for the reflection coefficient.

Errors in the following individual determinations contribute to the over-all error: position of the minimum, slope of the σ_m *vs.* r curve, shape

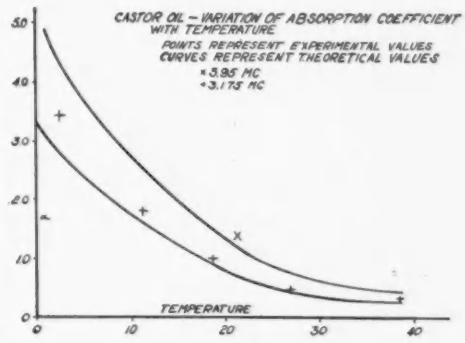

Fig. 5.

of the crevasse curve, value of the frequency. Adding the estimated error for each of these we arrive at a limit of error of about 20 percent. However, because of the unknown effect of satellite dips, and further, because of the possibility of nonparallelism between the crystal and the reflector affecting the shape of the crevasse, it is felt that it is not safe to say that the limit of error is less than 30 percent.

Discussion of Results

The theoretical absorption due to viscosity and heat conduction is:

$$\alpha = 2\eta\omega^2/3\rho v^3 + a^2KT\omega^2/2\rho vC^2,$$

where η = viscosity; $\omega = 2\pi f$, where f is the frequency; v = velocity of sound in the medium; a = coeff. of expansion at constant pressure; K = thermal conductivity; C = specific heat; T = absolute temperature.

The second term, for the liquids used, is of the order of magnitude of 1×10^{-5} of the value of the first, and this is negligible compared to the degree of accuracy of the experiment. Accordingly, a curve of the values of

$$2\eta\omega^2/3\rho v^3$$

was plotted for different temperatures at the same frequency, and the experimental results were compared with the curves. For the liquids used, the change of the viscosity with temperature is great. The agreement with the theoretical values, compared to that found by experimenters in low viscosity liquids, is good. This agreement of the measured and theoretical values may be seen from the α *vs.* T curves. The deviation is at

TABLE I.*

T°C	$\nu\times10^{-6}$	α	γ	λ_{CM}	v M/SEC.	$\alpha/\nu^2\times10^{-17}$
			Olive oil			
0.1	3.157	0.27	0.89	0.048	1510	2700
9.0	"	0.19	0.89	0.0473	1490	1900
21.7	"	0.135	0.88	0.046	1440	1350
36.4	"	0.06	0.92	0.0445	1400	600
54.5	"	0.045	0.90	0.043	1360	450
21.6	3.95	0.96	0.93	0.0365	1440	1250
			Castor oil			
2.7	3.157	3.4	0.67	0.0498	1570	34000
12.2	"	1.82	0.80	0.0485	1530	18200
18.6	"	1.09	0.77	0.0477	1500	10900
27.0	"	0.52	0.89	0.0468	1470	5200
37.0	"	0.37	0.91	0.0455	1430	3700
21.6	3.95	1.35	0.86	0.0381	1500	8400
			Glycerin			
14.0	3.157	0.44	0.61	0.0610	1930	4400
21.7	"	0.27	0.64	0.0604	1910	2700
34.0	"	0.08	0.83	0.0597	1885	800
50.0	"	0.058	0.80	0.0583	1840	580
21.6	3.95	0.49	0.90	0.048	1910	4900
			Linseed oil			
0.1	3.157	0.13	0.89	0.0485	1520	1300
10.5	"	0.096	0.89	0.0475	1490	960
20.5	"	0.058	0.92	0.0465	1470	580
36.2	"	0.040	0.85	0.0455	1430	400

* The following are approximate precision limits of tabulated quantities: α, ±8 to 20 percent; γ, ±1 to 5 percent, λ, ±1.0 qercent; v, ±1.0 percent; $\alpha/\nu^2\times10^{-17}$, ±8 to 20 percent.

all times less than 30 percent, the possible experimental error, so that there is no sign of any absorption due to slowness of energy interchange. See Figs. 2–5 and Table I.

Besides the explanations mentioned in the introduction for the good agreement in contrast to other data, another is of interest. Bergmann,[10] remarking on the fact that absorption in alcohol, to toluol and xylol depends on sound intensity, says that this increase in absorption may be caused by the formation of bubbles which are scarcely visible. This is a possible explanation of the much closer approach to theoretical values found in the present investigation, since the voltage applied across the crystal faces was of the order of magnitude of one volt, as compared to several thousand volts used in Sorensen's[1] investigation.

No such agreement was found, in general, with theory in the reflection coefficients. This same wide divergence was found by Fox[6] in his experiments on water.

No velocity measurements could be found in the literature for olive oil and linseed oil, but at approximately the same temperature, Parthasarathy,[11] using an optical method, gives 1986 meters/sec., where the present investigation finds 1910±15. This measurement was checked again and again with samples of Baker's C.P. glycerin, and no different value could be found. However, recently, two other measurements have been published. Data by Zachoval[12] seem to agree well with ours, although he used slightly different frequencies and temperatures. He finds at 21.9°, 1920 m/sec. for 2 megacycles, and 1888 m/sec. for 6 megacycles. For castor oil he finds, at 18.5°, 1483 at 2 megacycles, and 1496 at 6 megacycles, which also seems to agree well with our measurements within our accuracy.

The author wishes to acknowledge his indebtedness to Associate Professor Rock for suggesting the problem and directing the investigation, and to him and Professor Herzfeld for their advice during its solution; to Dr. Fox who lent his assistance most willingly at all stages of the problem; and to the Knights of Columbus, whose generosity made possible the graduate studies of the author.

[10] L. Bergmann, *Ultrasonics* (John Wiley and Sons, New York, 1938).

[11] S. Parthasarathy, Proc. Ind. Acad. Sci. **A2**, 497 (1935); **A3**, 385, 482, 519 (1936); **4**, 213 (1936).

[12] L. Zachoval, J. de phys. et rad. [VII] **10**, 350 (1939).

Uniphase Unidirectional Microphones*

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(Received April 20, 1941)

The unidirectional microphone is treated as a generalized transducer and network which are subjected to sound waves at two points in space. Network relationships are derived to produce unidirectional operation. These relationships are fulfilled in the "uniphase" structure which has a single transducer and a phase-shifting network instead of the two transducers normally used in unidirectional microphones. Acoustical phase-shifting networks applied to a diaphragm-type piezoelectric microphone and to a moving coil dynamic microphone producing a cardioid-type polar pattern are described.

INTRODUCTION

DEVELOPMENT of the "Uniphase" system of unidirectional operation of microphones was the result of an attempt to obtain a cardioid-type directional pattern with a single electroacoustic transducer, as contrasted with the two transducer systems conventionally employed. The term "Uniphase" is coined from the words "unidirectional" and "phase" denoting a system in which unidirectional properties are obtained through the action of phase-shifting networks on a single electroacoustic transducer.

Unidirectional microphones were first introduced in 1933 by Weinberger, Olson and Massa[1] who described a cardioid-type microphone consisting of a series arrangement of a velocity type ribbon and a labyrinth terminated pressure ribbon. In the following years various cardioid microphones have been made commercially available employing that principle, but consisting of other types of transducers, such as the piezoelectric crystal,[2] moving coil,[3] condenser,[4] etc. No attempt will be made here to discuss any of these structures as they have been described fully elsewhere.[5]

Directional properties of the "Uniphase" are dependent upon the phase-shifting action of acoustical networks which are applicable to a variety of electroacoustic transducers. In this paper are described a diaphragm-type piezoelectric microphone and a moving coil dynamic microphone employing the "Uniphase" system. These microphones were first made commercially available in 1937 and 1938, respectively.

THEORY

It appears that a microphone capable of unidirectional operation at wave-lengths considerably greater than the dimensions of the instrument should comprise some means responsive to the sound wave at two points in space; the response of these means is applied to an electroacoustical network capable of producing an electrical output dependent upon the intensity and phase position of sound at the points. Such mechanism is shown in Fig. 1. Let the sound responsive means be located at a and a', separated by a distance d. The functions A_θ and A'_θ delivered to the linear network N are the result of the sound wave arriving from an angle θ. The network output appears as a current i_θ through the output impedance Z. Since the network is linear,

$$i_\theta = PA_\theta - QA'_\theta, \tag{1}$$

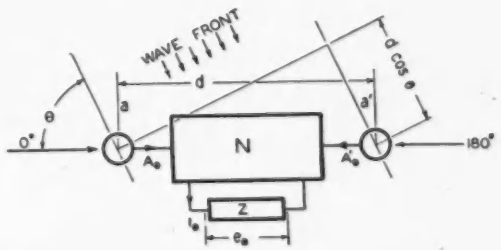


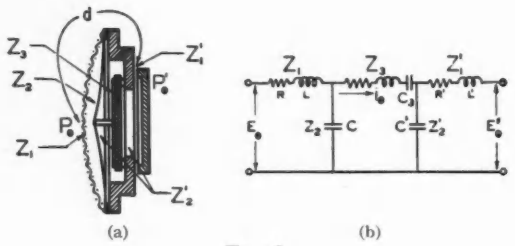
FIG. 1.

* Presented at the Chicago Meeting of the Acoustical Society of America, October 16, 1940.
† Chief Engineer, Shure Brothers, Chicago, Illinois.
[1] Weinberger, Olson and Massa, J. Acous. Soc. Am. **5**, 139 (1933).
[2] A. L. Williams and J. P. Arndt, Electronics, 242–243 (Aug. 1935).
[3] Marshall, Bell Lab. Rec. **17**, 338 (July, 1939).
[4] A. E. Swickard, U. S. Patent 2,093,664.
[5] R. P. Glover, J. Acous. Soc. Am. **11**, 296 (1940).

where P and Q are coefficients involving the network elements, and the subscripts indicate the angle of sound incidence; or, rewriting,

$$i_\theta = P\left(A_\theta - \frac{Q}{P}A'_\theta\right). \tag{2}$$

In a cardioid unidirectional microphone, the current through the output impedance should reduce to zero for sounds arriving from the rear. Hence



(a) (b)

FIG. 2.

$i_{180} = 0$. Therefore,

$$Q/P = A_{180}/A'_{180}. \tag{3}$$

Equation (3) establishes the general relation between the network elements which is required to produce unidirectional operation. Two of the networks capable of fulfilling Eq. (3) are described in a later part of this paper.

The directional properties of such a mechanism will now be analyzed. For the sake of simplicity, A and A' are assumed to be of equal magnitude, although this is not a necessary condition. From inspection of Fig. 1, A leads A' by an angle $\phi = (\omega d/c)\cos\theta$, where c is the velocity of sound. Then $A_\theta = A'_\theta \exp[j(\omega d/c)\cos\theta]$. Substituting this into Eq. (3),

$$Q/P = \exp(-j\omega d/c). \tag{4}$$

Equation (4) indicates that if the waves transmitted by the sound responsive means are of equal magnitude and differ in phase only, the network N should provide a phase shift proportional to frequency. Substituting Eq. (4) into Eq. (2),

$$i_\theta = P[A_\theta - A'_\theta \exp(-j\omega d/c)] \tag{5}$$

and inserting the value of A given above,

$$i_\theta = PA'(\exp[j(\omega d/c)\cos\theta] - \exp[-j\omega d/c]). \tag{6}$$

The exponentials may be expanded into their cosine and sine terms using the equation $\exp(j\phi) = \cos\phi + j\sin\phi$. For small values of ϕ the cosine terms approach unity and cancel out, while the sine terms become approximately equal to the angle, and add up; therefore,

$$i_\theta = PA'(\omega d/c)(1+\cos\theta). \tag{7}$$

If the magnitudes of A and A' are independent of the angle of incidence, the directional response of the system approximates a cardioid of revolution.

UNIDIRECTIONAL CRYSTAL MICROPHONE

The structure of a Rochelle salt crystal microphone and acoustical network embodying the "Uniphase" principle is shown in Fig. 2(a). The diaphragm is of a curvilinear shape to increase the driving point rigidity and reduce the edge stiffness. A light drive-link connects the diaphragm to the bimorph Rochelle salt crystal[6] which is fastened to the reference frame in such a manner that motions of the diaphragm result in deflections of the crystal.

The circular enclosure containing the crystal has a back cover forming an annular outlet to the atmosphere, and having an impedance $Z'_1 = R' + j\omega L'$.[7] This outlet together with the volume within the enclosure provides practically all the phase shift required for unidirectional operation. The front screen has an impedance $Z_1 = R + j\omega L$, and taken together with the volume in front of the diaphragm it provides high frequency response control of the microphone. The pressure at the front screen is P_θ and the pressure

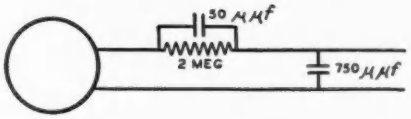
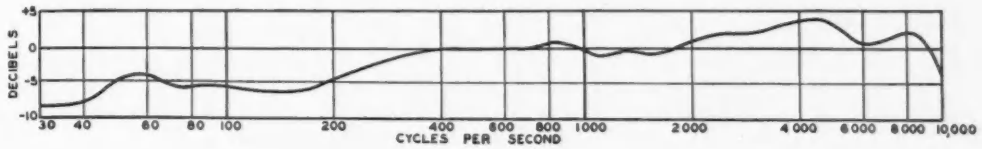


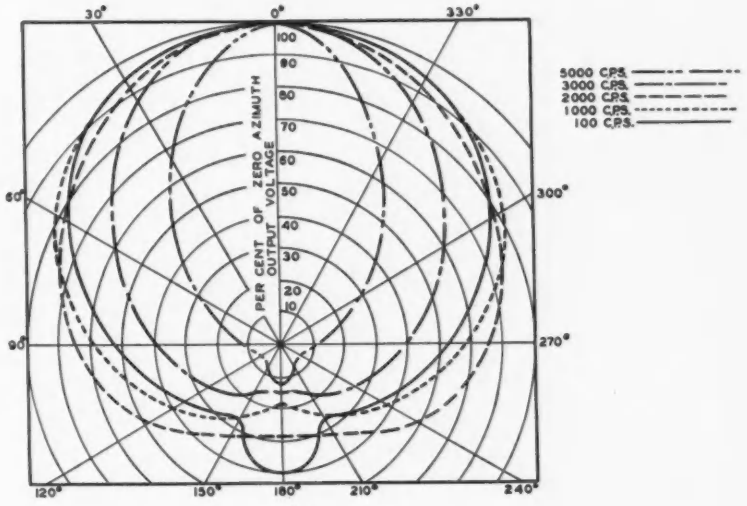
FIG. 3. Response correcting network.

[6] C. B. Sawyer, "The use of Rochelle salt crystals for electrical reproducers and microphones," Proc. I.R.E. **19**, 2020 (1931).

[7] Reference is here made to acoustical impedances, which in the c.g.s. system are given by the following expressions: Impedance of a slit: $Z = (12\mu w/t^3 l) + j(6\rho w\omega/5lt)$ where μ is the viscosity coefficient of the medium, ρ density of the medium, t is the thickness of the slit, w is the width of the slit (in the direction of the fluid flow), and l is the length of the slit (across the direction of fluid flow); impedance of a cavity of volume v: $Z = 1/j\omega C_a$ where $C_a = v/\rho c_v^2$ and c_v is the velocity of sound in the medium. Acoustical impedance of a mechanical system consisting in part of a diaphragm with an area A is given by Z_m/A^2, where Z_m is the mechanical impedance of the system.



(a)



(b)

FIG. 4. Unidirectional crystal microphone: (a) typical frequency response, (b) typical polar response.

at the outlet is P'_θ. The effective acoustical distance from the diaphragm to the slit is called d.[8]

The equivalent electrical circuit of this microphone is shown in Fig. 2(b). In this circuit the conventional analogy is used, i.e., voltages E_θ and E'_θ replace pressures with corresponding subscripts, and currents indicate volume velocities. Solving for the diaphragm velocity, i_θ,

$$i_\theta=\frac{(1+Z'_1/Z'_2)E_\theta-(1+Z_1/Z_2)E'_\theta}{Z'_1\left(1+\frac{Z_1}{Z_2}\right)+Z_3\left(1+\frac{Z_1}{Z_2}\right)\left(1+\frac{Z'_1}{Z'_2}\right)+Z_1\left(1+\frac{Z'_1}{Z'_2}\right)}. \quad (8)$$

Comparing Eqs. (8) and (1), it is evident that P is equivalent to the coefficient of E_θ divided by the denominator, and Q is equivalent to the coefficient of E'_θ divided by the denominator. Assuming front and rear pressures to be equal and displaced by the angle $\omega d/c$, Eq. (4) may be rewritten

$$P/Q=\frac{1+Z'_1/Z'_2}{1+Z_1/Z_2}=\frac{1-\omega^2L'C'+j\omega C'R'}{1-\omega^2LC+j\omega CR}$$
$$\approx\exp(j\omega d/c). \quad (9)$$

Let L and L' be chosen so that $L=CR^2/2$, and $L'=C'R'^2/2$. Substituting these values into Eq. (9), it is observed that the real parts in both the numerator and the denominator are the first two terms of the cosine series expansion, while the imaginary parts in the numerator and the denominator are the first terms of the sine expansion. Hence, for sound waves having a wavelength considerably larger than the dimensions of the instrument, Eq. (9) may be set with a good degree of approximation,

$$\frac{\cos\omega C'R'+j\sin\omega C'R'}{\cos\omega CR+j\sin\omega CR}=\frac{\exp(j\omega C'R')}{\exp(j\omega CR)}$$
$$=\exp(j\omega d/c) \quad (10)$$

and hence,

$$(C'R'-CR)=d/c. \quad (11)$$

[8] There is no accurate mathematical expression for this distance. d is roughly equal to the shortest air path from the center of the diaphragm to the slit. However, the effective acoustical distance d may be determined with good accuracy by adjusting the network elements until the desired directional effect is obtained, and substituting the values of the acoustical elements into Eq. (11).

The choice of network elements indicated in Eqs. (9) to (11) determines the unidirectional operation of the microphone. The approximations involved with the assumption that the microphone is small compared with the wavelength are of no practical significance for $\lambda > 2\pi d$. At shorter wave-lengths the microphone becomes pressure operated and its directional properties are then principally due to diffraction.

The frequency response of this microphone may be found by multiplying Eq. (8) by $1/jwC_3$ where C_3 is the equivalent acoustical compliance of the crystal element.[7] Through appropriate choice of network constants, the voltage developed in the crystal rises with frequency at the rate of 6 db per octave up to approximately $\lambda = 2\pi d$ and is constant thereafter. Uniform frequency response is then obtained at the terminals of the microphone through the use of an electrical network which has an inverse transmission characteristic, shown in Fig. 3. In the commercial form of this microphone the network takes the form of a parallel combination of condenser and resistor in series with the cable connecting the microphone to the amplifier. The 0° incidence frequency response and polar patterns at various frequencies in a spherical field are shown in Fig. 4(a) and 4(b).

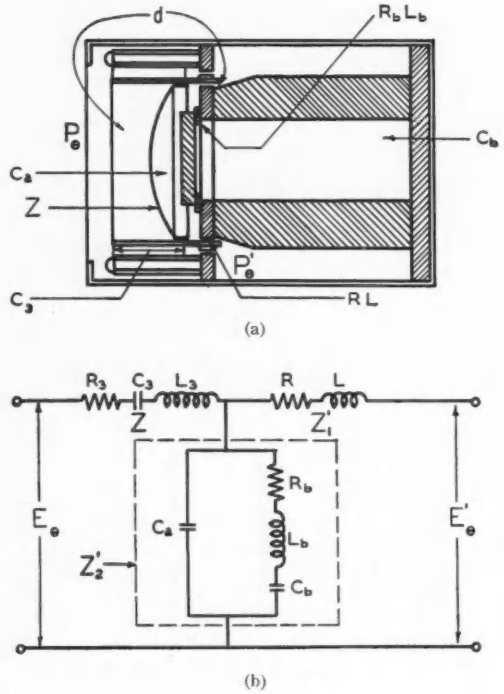


FIG. 5.

UNIDIRECTIONAL DYNAMIC MICROPHONE

A moving coil microphone employing the "Uniphase" is shown in Fig. 5(a). The coil is wound on an elongated form and suspended from two flexible spiders. For mechanical reasons, the space between the moving coil and the inner pole piece is used as one of the phase-shifting network elements. This space plays the counterpart of the annular passage shown in the piezoelectric microphone. However, considerations of minimum safe clearance between the coil and the pole-piece determine the maximum resistance-to-mass ratio of the passage, and necessitate a slight modification of the previous network scheme. It is found that by subdividing the inner volume into two portions connected by means of another passage having resistance and inertance (R_b and L_b), the network elements can be selected to give the required phase shift throughout practically all of the useful audiofrequency spectrum.

The electrical circuit corresponding to the acoustical structure is shown in Fig. 5(b). This circuit is similar to that of Fig. 2(b) with the exception that Z_1 and Z_2 are nonexistent. Hence, Eq. (8) may be employed to determine the network performance if $Z_1 = 0$, and $Z_2 = \infty$. The mechanical velocity of the moving element,

$$i_\theta = \frac{(1 + Z'_1/Z'_2)E_\theta - E'_\theta}{Z_3(1 + Z'_1/Z'_2) + Z'_1}. \tag{12}$$

Comparing Eqs. (12) and (1), it is evident that P is equivalent to the coefficient of E_θ divided by the denominator, and Q is equivalent to 1 divided by the denominator.

Substituting these values into Eq. (4),

$$\frac{P}{Q} = 1 + \frac{Z'_1}{Z'_2} = 1 - \omega^2 L'_1 C_a + j\omega R'_1 C_a + \frac{R'_1 + j\omega L'_1}{R_b + j(\omega L_b - 1/\omega C_b)} \approx \exp(j\omega d/)c. \tag{13}$$

There is no simple analytical solution for determining the approximate values of the network constants involved in Eq. (13) such as was found

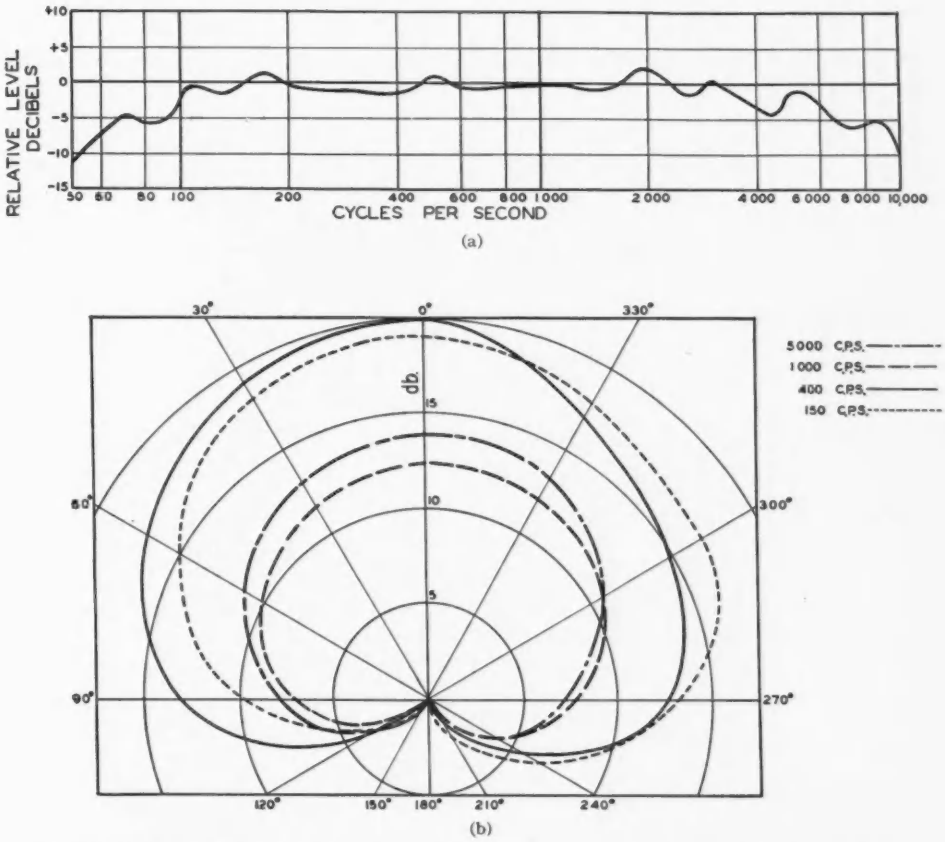


FIG. 6. Unidirectional dynamic microphone: (a) frequency response, (b) polar response.

in connection with Eq. (9). The elements are best determined through calculations involving certain simplifying assumptions, and trial substitution into Eq. (13). The constants required with a structure having a $d=3/4''$ provide correct phase-shifting effect up to approximately 4000 cycles per second. Above 4000 cycles the instrument becomes pressure operated, and it depends upon diffraction for its directional properties.

The voltage developed is proportional to the velocity of the coil. Since the net force upon the diaphragm increases with frequency, and the moving system is mass controlled throughout practically all of the frequency range, the voltage developed is substantially independent of frequency. Above the range of network operation the response tends to drop at the rate of 6 db per octave. This tendency is counteracted to a considerable extent by the tube at the front of the coil which provides an improvement in frequency response in the extreme high end of the useful frequency spectrum.

A plane field frequency response curve of this unit is shown in Fig. 6(a). The directional polar pattern is shown in Fig. 6(b). It is seen that the polar pattern closely approximates a cardioid, thus confirming the theory previously outlined.

ACKNOWLEDGMENT

The author wishes to express his gratefulness to Professor C. P. Boner, of the University of Texas, who performed the measurements of Fig. 6 in the outdoor measuring set-up of the University of Texas.

A General Purpose Vibration Meter

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General Radio Company, Cambridge, Massachusetts
(Received May 28, 1941)

THE field of use for any measuring instrument depends upon a large number of factors, many of which are all too seldom considered in the design. Of course, a measuring instrument must be accurate within the requirements of all normal applications. If it must be carried about it should also be small, light and easily portable. If its use is to become widespread the price also must not be excessive. Good instrument design includes a proper balance between these characteristics, so as to provide the greatest service to the greatest number of users.

The sound level meter is a good example of the close relationship between these design factors and the degree to which the instrument is adopted by industry in general. The advent of small, light, convenient and reasonably priced sound level meters changed sound measurements from a relatively unknown laboratory procedure which was carefully avoided by most industrial organizations into a common factory and laboratory test which few manufacturers would dare to overlook. The result has been the better design of various mechanical products and greater satisfaction on the part of consumers.

But these design factors alone do not tell the whole story. After an instrument is bought it must be used if it is to be of any benefit, and the degree to which it is used is not dependent solely upon the more obvious design factors such as the number and type of knobs or the size and shape of the case. To the user the characteristics of paramount importance are, then: "In what terms does the instrument read?" "Does it give me answers which mean something to me?" and "Does it tell me what I want to know in a minimum of time?"

Herein lies another secret in the sound level meter's success. For most purposes it provides a single answer which automatically takes into account the most important factors to be considered in evaluating a noise. For sales and purchasing organizations this is all that is necessary to make a fair comparison between the noise-producing characteristics of competing machines. For the manufacturer it provides all that is necessary for ordinary production tests.

Few will dispute that for some applications, particularly those connected with machinery design and engineering, additional data in the form of analyses are also required. For this reason additional analyzing equipment is available for use with sound level meters. But nevertheless it has become increasingly evident to those engaged in the manufacture, sale, or use of sound level meters that the ability of these instruments to give a single reading which might be called a single figure of merit regarding the equipment being tested is one of its most important advantages and accounts for probably 75 percent of the measurements taken with the meters.

Sound and vibration measurements are closely allied. The measurement of vibration is not a new idea, and devices for accomplishing this purpose have been available for many years. The degree to which they met the requirements of the application is open to considerable question, and it is certain that in many cases, at least, misinterpretation of the readings by users as well as misleading ratings as catalogued by the manufacturers of the measuring equipment have led to errors of serious magnitude. For instance, many common types of vibration measuring devices include mechanical vibrating systems having seriously resonant characteristics, thus limiting the frequency range over which they may be used. Nevertheless, in many applications attempts have been made to use these devices for measuring vibrations falling outside of the satisfactory frequency range, resulting in meaningless readings which have served only to confuse the users.

For some time vibration pick-ups have been supplied as accessories for use with sound level meters. In many cases they have been extremely useful, but naturally the low frequency range is

limited by the sound level meter, which was designed only for the audible spectrum. The fundamental vibrations in many types of machinery lie well below this range. Because of this there has been an insistent demand for vibration measuring equipment to operate at frequencies as low as 2 cycles. To meet this demand a vibration measuring counterpart of the sound level meter has been developed.

The present-day manufacturer of sound level meters has few decisions to make as to the basic characteristics of the instrument. Cooperation of manufacturers and users with the American Standards Association has resulted in definite specifications regarding the response of the sound level meters, so that various makes and models of modern design are as nearly alike in operating characteristics as the present state of the art allows. This is not the case in vibration measurements.

The engineer investigating the vibration measurement field is immediately impressed by the wide variety of equipments in use, by the great number of units in which the results are expressed, and by the fact that most instruments are usable only over a seriously restricted range of frequencies. In the design of the new vibration meter, therefore, an attempt has been made not only to simplify the design and operation, but also to provide easily understood units of measurement and an extended frequency range exceeding that required for practically all applications.

As a sound level meter has three weighting characteristics to take care of different level conditions, so it appears that a vibration meter also should have a corresponding variety of response characteristics in order to be a really general purpose instrument. The three characteristics of vibration which both usage and logic indicate as the most desirable for measurement are the displacement, the velocity and the acceleration. Since velocity is the derivative of displacement and acceleration, in turn, the derivative of velocity, these three characteristics differ by terms dependent upon the frequency of the vibration and hence are measured by circuits or devices having different frequency characteristics. The use of electrical circuits to perform the equivalent of integration or differentiation is fairly common. Such circuits generally consist of a reactive and a nonreactive component in order to perform a single stage of integration or differentiation.

Vibration pick-ups have been used for several years to extend the range of usefulness of sound level meters.[1] The vibration pick-up supplied by the General Radio Company for use with its sound level meter is equipped with a so-called "control box"[2] containing integrating networks which adjust the frequency response to provide measurements of these three main vibration characteristics over a range down to approximately 25 cycles.

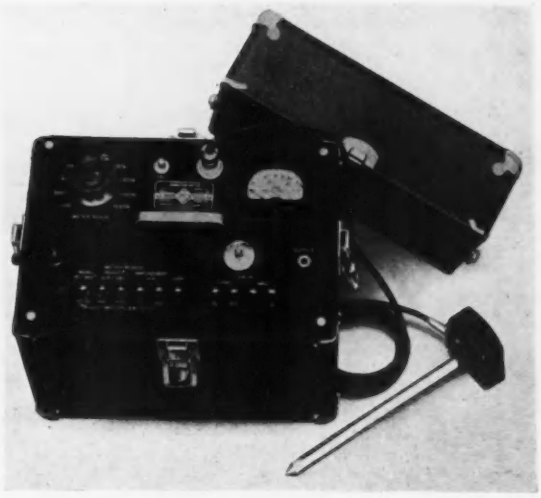


FIG. 1. The Type 761-A vibration meter is a light, portable instrument designed for measuring vibration acceleration, velocity, or displacement at frequencies down to 2 cycles per second.

The Type 761-A vibration meter (Fig. 1) has been designed for a usable range down to 2 cycles per second. An acceleration type piezoelectric pick-up is used because of its simplicity, freedom from objectionable resonances, stability and relatively low cost. The integrating or frequency-response-changing networks, which are of the series resistance-parallel capacitance type, are included in the amplifier circuits, so that they serve not only to provide the correct

[1] H. H. Scott, "Using the noise meter with a vibration pick-up," General Radio Experimenter, **9**, 1–2 (April, 1935).

[2] B. Baumzweiger, "Application of piezoelectric vibration pick-up to measurement of vibration velocity and displacement," J. Acous. Soc. Am. **11**, 303–307 (1940).

over-all response characteristics, but also to reduce and, in fact, substantially eliminate such common difficulties as tube hiss, microphonic noise, etc. The frequency-response characteristics extend smoothly up to 1000 cycles per second and are entirely usable for many purposes up to 2000 cycles per second, and it is possible to use smaller types of pick-ups for operation at even higher frequencies, should there be sufficient demand. A careful survey of the vibration measurements field has shown, however, that the range from 2 to 1000 cycles substantially exceeds all common applications for vibration measurements at the present time.

To provide this type of result some rather unusual characteristics are required. The amplifier is of the resistance-capacitance-coupled type, incorporating coupling circuits having unusually long time constants. Figure 2 shows

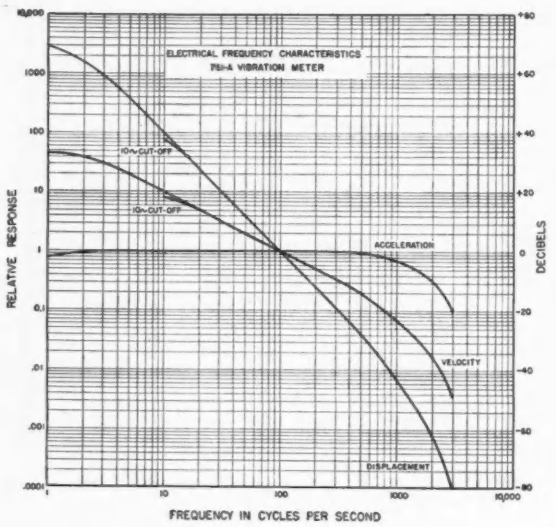
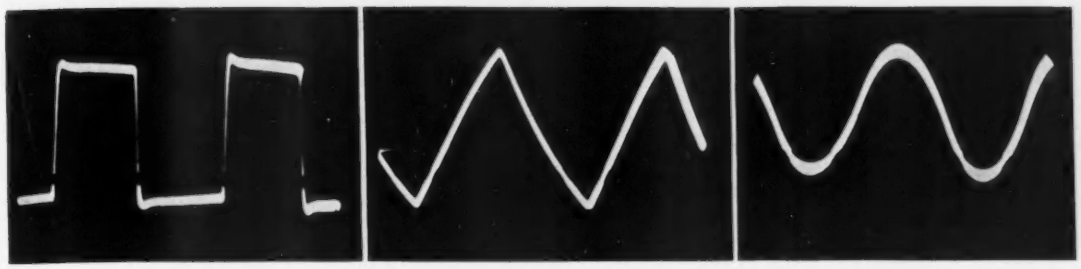


FIG. 2. Frequency-response characteristics of the amplifier and indicating instrument used in the Type 761-A vibration meter.

the frequency response of the electrical circuits for measurements of acceleration, velocity, and displacement. The high frequency deviation from a straight line compensates for a corresponding rise in the pick-up. Due to the loss in the integrating circuits a high degree of amplifier gain, approximately 140 decibels, must be maintained, and the response must be substantially flat down to 2 cycles. The curves labeled "10-cycle cut-off" represent an additional feature of the instrument which provides supplemental integrating networks for applications involving only frequencies above 10 cycles. This allows an additional tenfold increase in sensitivity for measuring low amplitude vibrations above 10 cycles, such as occur, for instance, in clocks, speedometers, and other small mechanisms. The performance of the integrating circuits is shown graphically in Fig. 3. The oscillograms show the transmission of a 60-cycle square wave through the complete amplifier with the various integrating networks in the circuit.

The average over-all frequency response of the vibration meter including the pick-up is shown in Fig. 4. Comparison of these characteristics with those of the usual run of vibration-measuring devices will readily indicate the high degree of superiority of the new vibration meter in regard to wide range frequency response. The sensitivity ranges covered by the new vibration meter are 16 micro-inches to 30 inches for displacement, 160 micro-inches per second to 300 inches per second for velocity, and 0.16 inch per second per second to 3900 inches per second per second (approx. 10 *g*) for acceleration. The wide ranges of frequency and intensity covered by the instrument provide an unusually high degree of adaptability to various vibration problems.

In many respects the design of the vibration meter follows closely that of the Type 759 sound level meters, which have proved their value in innumerable applications. For instance, the amplifier, including all tubes, is mounted, together with some of the heavier circuit components, on a resilient rubber suspension, thus providing an effective vibration filter to insure freedom from microphonic difficulties or damage to the tubes during rough handling of the instrument. The general construction of the instrument is shown in Fig. 5. The amplifier circuit is of the stabilized type, which is relatively unaffected by normal running down of the batteries. The attenuator which adjusts the sensitivity is of the two-section type, allowing all amplifying stages to operate with a maximum of efficiency and a minimum of noise. The indicating instrument is of the shaped-polepiece type, providing a semi-logarithmic scale and having special slow motion characteristics to provide satisfactorily steady readings even at 2 cycles. An internal calibration



(a) (b) (c)

FIG. 3. Illustration of the integration of a 60-cycle square wave by the amplifier and integrating circuits. (a) Acceleration response, (b) velocity response, (c) displacement response.

system is included whereby the gain of the amplifying circuits is checked readily against a built-in attenuator, thus allowing compensation to be made for long-time changes due to tubes, circuit components, or batteries. A suitable voltage for the calibrating procedure may be obtained from any alternating-current power outlet from 90 to 240 volts and of any power frequency.

In addition, several innovations are introduced which improve the convenience of operation. For instance, the integrating networks are controlled by a push-button switch, as are also the calibrating circuits. This allows rapid changing from one integrating network to another, and the calibration procedure may be quickly carried out and is a simplification over the already convenient system used in the sound level meter. The use of dry electrolytic condensers of more than ample capacity for all by-passing applications results in a high degree of stability, freedom from motorboating, or unwanted regeneration or degeneration, and a tremendous reduction in weight over what would be required with other condenser types. Provision is made for mounting in the cover of the instrument the vibration pick-up, together with its cable, the calibrating cable, and various extra probes for the pick-up. All instructions are also mounted permanently inside of the cover.

The units in which the instrument reads have been selected as a result of a careful survey of the field, the units already in use, and the present confusion over conflicting types of scales. To begin with, it was decided that inches and seconds were the logical basic units. The term "g," meaning the acceleration of gravity, which is frequently used for acceleration readings was purposely rejected in order that the acceleration, velocity, and displacement characteristics might all read in similar units. The meter, therefore, reads acceleration directly in inches per second per second, velocity in micro-inches per second, and displacement in micro-inches. The attenuator switch is labeled "Meter Scale" and reads in terms of full-scale meter deflection for each setting. The multiplying factors associated with the various integrating networks are equal multiples of ten, so that they merely mean moving the decimal point one way or the other. All readings are calibrated with respect to r.m.s. values, so that on a single frequency vibration merely multiplying the displacement reading by 2π times the frequency gives the velocity, and, similarly, multiplying the velocity

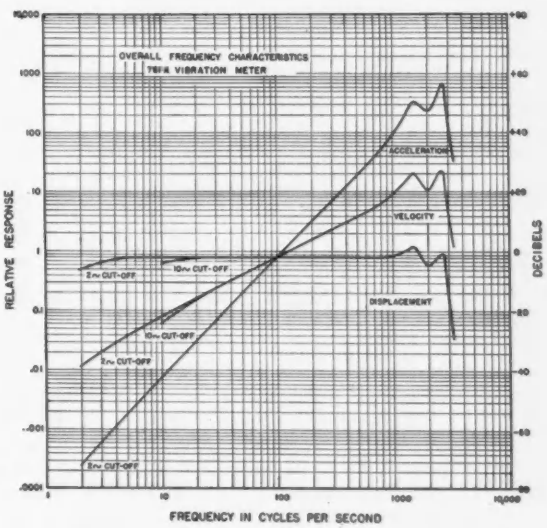


FIG. 4. Over-all frequency *versus* amplitude characteristics of the Type 761-A vibration meter, including an average pick-up.

reading by 2π times the frequency gives the acceleration. It will be readily seen that the widespread confusion and cumbersome conversion factors required by many other types of calibrations involving g's and combinations of peak, average, or r.m.s. readings are substantially eliminated by this method of calibration. The use of these other systems is not necessarily excluded for those users who wish to express the data in other terms. It was considered of far more importance, however, that various readings taken on this one instrument should be simply related in terms of frequency, rather than that any attempt should be made to incorporate all of the other scales and units which have been used in certain applications.

The actual calibration of the vibration meter in the General Radio Company's standardizing laboratory a precision motor-driven mechanical vibrator is used. The vibrator is of the eccentric type, carefully machined and manufactured so as to produce essentially sinusoidal vibration. The frequency can be changed by varying the motor speed with a Variac. High frequency checks on the vibration pick-ups have been made by means of electrodynamic and piezoelectric vibrators to insure satisfactory response over the entire range of the instrument.

In actual use the vibration meter has more than proved its value, both in accuracy and convenience. The best illustration of its actual usefulness is the fact that it is in almost constant use in those laboratories where it is already available. Like the sound level meter, it gives for most purposes a single answer without the necessity of laborious or inconvenient computations or corrections. Its frequency range is wide enough so that this factor can generally be forgotten entirely. It reads in units which everyone understands, and its method of operation is such as to require a minimum of skill or experience. Although only a limited number of these instruments have so far been delivered, they are already proving their value in the automotive, aeronautic, and various other mechanical manufacturing and engineering fields.

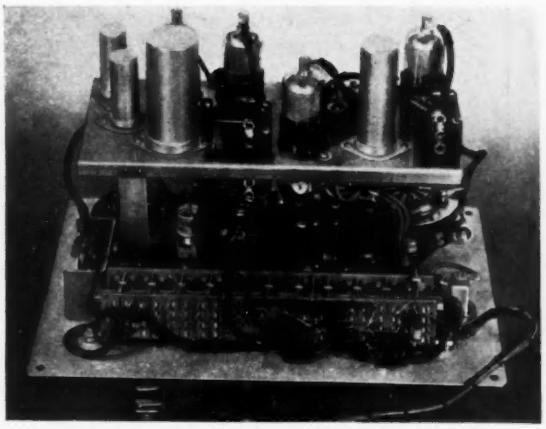


FIG. 5. Internal construction of vibration meter, showing amplifier suspension.

Ball Bearing Noise and Vibration

WALTER T. BUHL
S K F Industries, Inc., Philadelphia, Pennsylvania
(Received May 28, 1941)

IN their campaign to eliminate noise from small appliances, manufacturers are demanding quieter component parts. In the past, considerable work has been done to quiet existing designs. Today, however, the tendency is to design the noise out of the machine before it is built. This means that each possible source of noise must be considered and the noise from each part held to a minimum.

Because the parts manufacturer must have a knowledge of how his unit will act in a given installation, S K F has carried out research under the direction of Dr. H. Styri on antifriction bearing noise, and especially on small ball bearings. Ball bearings are not generally considered noisy, but there are a few installations which at first are not as quiet as they should be. Therefore, a better understanding of the mechanism of ball bearing noise will help in new designs and in diagnosing noisy installations. There is no ball bearing that is strictly silent, but *good* bearings can be applied so that their effect on the general noise level of the machine is imperceptible.

In the old days, the method of determining whether or not a ball bearing was noisy, consisted of spinning the bearing by hand and holding it close to the ear. This test is now considered inaccurate for it has been learned that lubrication determined the noise by the damping it gave the parts as they struck each other, and the distance to the ear varied enough so that an accurate determination could not be made. Further, this test was far from actual running conditions.

A basic fault in this test is that in a typical ball bearing installation there is no direct radiation from the bearing to the listener's ear. In Fig. 1 is a small bearing application showing an enclosure dictated by cleanliness and lubrication and which turns out to be the best acoustical enclosure that can be made. The only possible noise leak is along the shaft, but this is effectively sealed by the felt packing. In an installation like this, appreciable bearing noise must be transmitted to the ear by some other means than directly from the bearing parts. It is obvious there can be no "cage rattle." There may be a possibility of ball and race noise because the largest portion of bearing noise originates in the bearing as vibration and is transmitted through

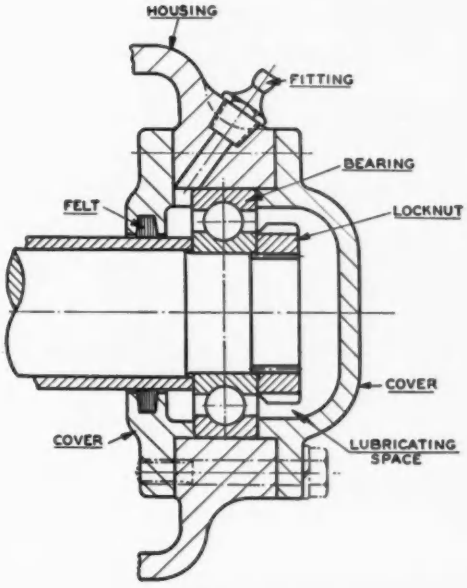


FIG 1.

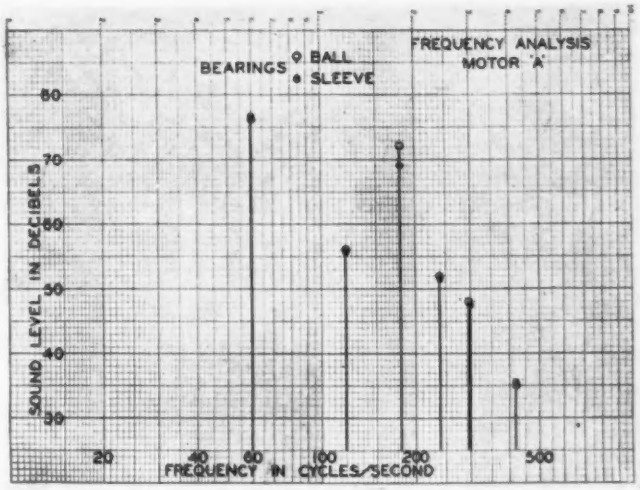


FIG. 2.

reading by 2π times the frequency gives the acceleration. It will be readily seen that the widespread confusion and cumbersome conversion factors required by many other types of calibrations involving g's and combinations of peak, average, or r.m.s. readings are substantially eliminated by this method of calibration. The use of these other systems is not necessarily excluded for those users who wish to express the data in other terms. It was considered of far more importance, however, that various readings taken on this one instrument should be simply related in terms of frequency, rather than that any attempt should be made to incorporate all of the other scales and units which have been used in certain applications.

The actual calibration of the vibration meter in the General Radio Company's standardizing laboratory a precision motor-driven mechanical vibrator is used. The vibrator is of the eccentric type, carefully machined and manufactured so as to produce essentially sinusoidal vibration. The frequency can be changed by varying the motor speed with a Variac. High frequency checks on the vibration pick-ups have been made by means of electrodynamic and piezoelectric vibrators to insure satisfactory response over the entire range of the instrument.

In actual use the vibration meter has more than proved its value, both in accuracy and convenience. The best illustration of its actual usefulness is the fact that it is in almost constant use in those laboratories where it is already available. Like the sound level meter, it gives for most purposes a single answer without the necessity of laborious or inconvenient computations or corrections. Its frequency range is wide enough so that this factor can generally be forgotten entirely. It reads in units which everyone understands, and its method of operation is such as to require a minimum of skill or experience. Although only a limited number of these instruments have so far been delivered, they are already proving their value in the automotive, aeronautic, and various other mechanical manufacturing and engineering fields.

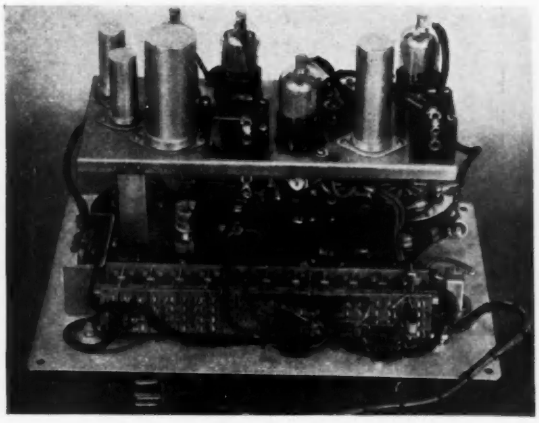


FIG. 5. Internal construction of vibration meter, showing amplifier suspension.

Ball Bearing Noise and Vibration

WALTER T. BUHL
S K F Industries, Inc., Philadelphia, Pennsylvania
(Received May 28, 1941)

IN their campaign to eliminate noise from small appliances, manufacturers are demanding quieter component parts. In the past, considerable work has been done to quiet existing designs. Today, however, the tendency is to design the noise out of the machine before it is built. This means that each possible source of noise must be considered and the noise from each part held to a minimum.

Because the parts manufacturer must have a knowledge of how his unit will act in a given installation, S K F has carried out research under the direction of Dr. H. Styri on antifriction bearing noise, and especially on small ball bearings. Ball bearings are not generally considered noisy, but there are a few installations which at first are not as quiet as they should be. Therefore, a better understanding of the mechanism of ball bearing noise will help in new designs and in diagnosing noisy installations. There is no ball bearing that is strictly silent, but *good* bearings can be applied so that their effect on the general noise level of the machine is imperceptible.

In the old days, the method of determining whether or not a ball bearing was noisy, consisted of spinning the bearing by hand and holding it close to the ear. This test is now considered inaccurate for it has been learned that lubrication determined the noise by the damping it gave the parts as they struck each other, and the distance to the ear varied enough so that an accurate determination could not be made. Further, this test was far from actual running conditions.

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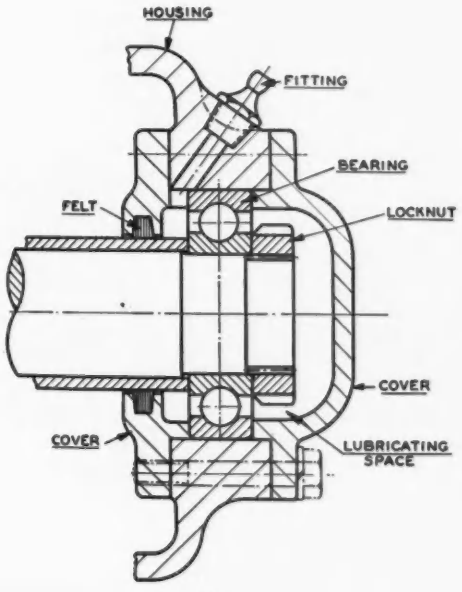

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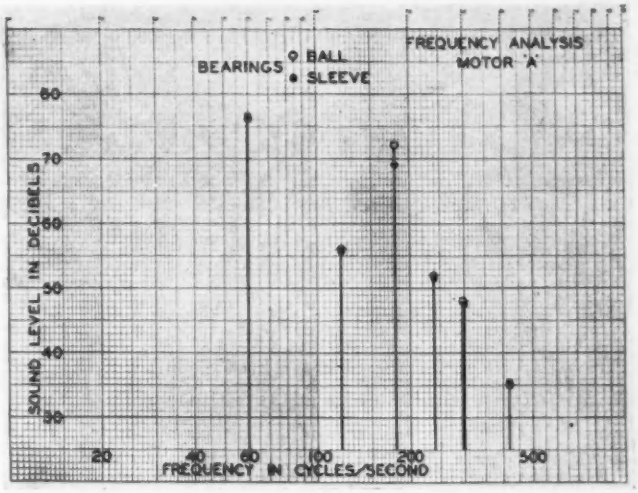

FIG. 2.

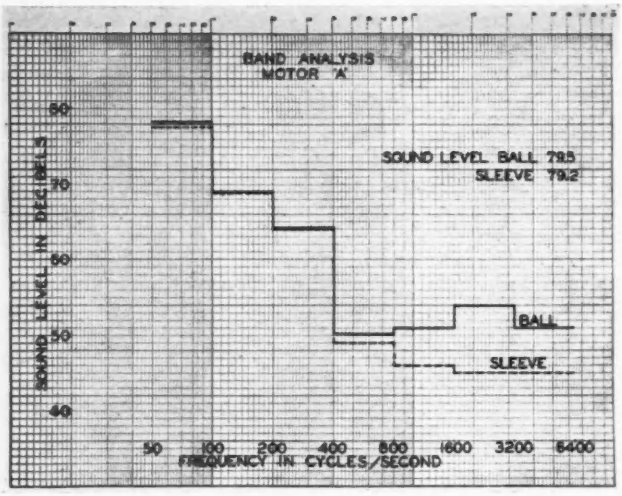

FIG. 3.

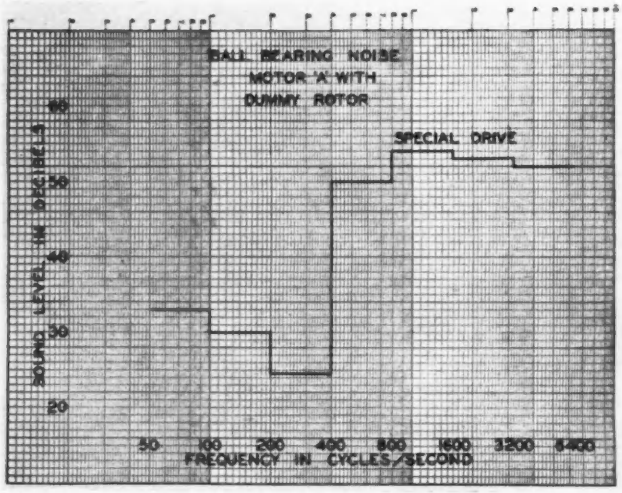

FIG. 4.

the bearing seat with the machine acting as the sound radiator. In short, the problem of ball bearing noise depends on two factors: the transmission of vibration and its subsequent radiation as sound which accounts for the discrepancies between the old listening tests and noise from the bearing in service.

In order to verify this analysis a series of tests was made on two types of $\frac{1}{2}$-hp motors. A microphone was mounted two inches away from the end of the shaft, and a frequency analysis made on motor "A," first with plain bearings, then with ball bearings, (Fig. 2). A comparison of the most prominent notes shows no important difference between the two types of bearings. All the notes can be accounted for as resulting from the electrical stresses (60, 120, 180, 300, 420, c.p.s.) or noise from the rotor fan (240 c.p.s.). Above 500 c.p.s. no prominent notes could be found, but in sweeping the analyzer through these frequencies we discovered erratic readings above the normal level of room noise. This region was filled with notes which constantly changed frequency and amplitude and could not be followed with a 1 percent band width analyzer.

With octave band pass filters, a re-run of this test clearly showed the difference between the two types of bearings, (Fig. 3). This new analysis indicated variations up to 9.0 decibels although the difference in total level was only 0.3 decibel. The wide-band analysis gave steady readings which were reproducible to 0.5 decibel. The lack of notes above 500 c.p.s. was verified later with a high speed recording analyzer.

Below 500 c.p.s. the bearing noise was marked by the prominent motor notes. To investigate this region for bearing noise, we fitted a dummy rotor to the motor and used a belt drive. With this set-up the band analysis showed a sudden drop in level at 400 c.p.s. (Fig. 4), a drop or cut-off that could occur anywhere between 400 and 800 c.p.s. due to the band width. The cause of the cut-off is the sharp drop in sound radiating efficiency when the size of the radiator is smaller than one-half a wave-length. As this motor is about eleven inches in diameter, this would place the cut-off at 600 c.p.s.

This principle, used in rubber-mounted motors, greatly reduces the low frequency noise normally radiated from a large machine base. In the rubber-mounted pillow-block made for ball bearings and used on fans and ventilating equipment, bearing vibration is almost completely isolated. The small amount of noise radiated from the bearing shell is only in the high frequencies which are easily absorbed.

Because of the unpitched characteristics of vibrations generated by ball bearings, it is evident any resonant frequency of the appliance in the audible range tends to be excited. In most instances, the amplitude of vibration of the bearing is so small it cannot overcome the internal damping of the machine. We have discovered a few installations where a pronounced mechanical resonance exists with little damping and in these instances a note may be heard. Speed variations do not change the pitch of the note although there is a marked change in intensity. This leads to the conclusion that while a smooth running ball bearing seldom eliminates a resonance condition, a very small change in design often destroys the resonance and completely removes the noise. Stiffening some of the parts is generally sufficient, but sometimes it is necessary to use a material with a higher internal damping.

Two of the most frequent causes of excessive bearing vibrations are dirt and denting. The increased vibration of a dirty bearing (Fig. 5) correlates well with the increase in noise of that bearing in use, (Fig. 6). This is shown in the noise analysis of Motor B which was equipped, respectively, with clean and dirty bearings. Motor B was quite sensitive to the quality of bearing installed. A 2.0 db increase in bearing noise over the quiet condition was objectionable so the quality of bearings supplied to the manufacturer had to be held to definite noise limits.

The other cause of bearing noise, "ball denting," is produced by a blow on the bearing causing slight denting of the polished raceways by the balls. These dents are evenly spaced, giving a vibration of a definite frequency that can be computed from the speed, bearing dimensions and number of balls. Varying the speed varies the frequency. Misalignment of bearing parts acts in the same manner as ball denting.

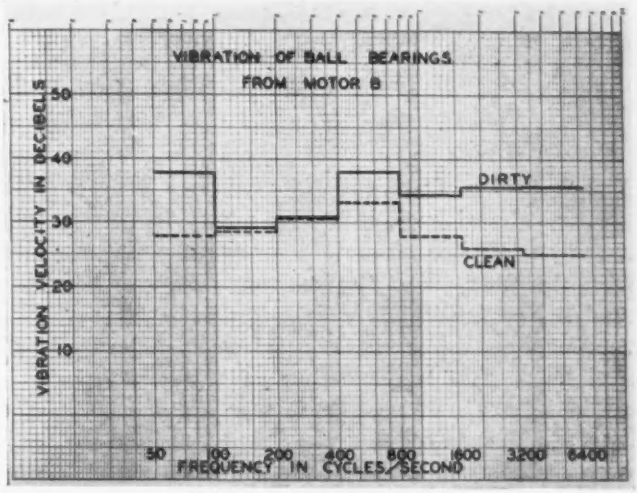

FIG. 5.

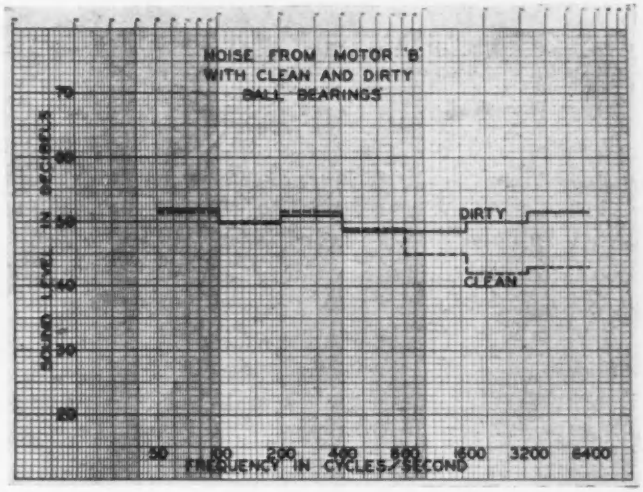

FIG. 6.

Physical Properties of Wood for Violin Construction

R. B. ABBOTT AND G. H. PURCELL
Physics Department, Purdue University, Lafayette, Indiana
(Received May 21, 1941)

IN the design of musical instruments, especially the stringed ones, it is desirable to know as much as possible about the properties of the materials from which the instruments are to be made. For example, it is necessary to use thoroughly seasoned wood in the construction of a violin so that the completed instrument will retain its shape. Also, the material of the top of a violin should be strong for its weight so that it can support the load due to the tension in the strings and yet not be too heavy to vibrate freely. The color and grain of the wood determine the artistic more than the tonal effects.

The following physical properties of wood were first studied: moisture content, density, elasticity, and resistance to motion of vibration. It was found that each property varied widely from specimen to specimen taken from a single sample of wood. Therefore, it was necessary to determine all the properties for each specimen and take average values. In this work, ten or more specimens were taken from a large sample for each variety of wood tested.

In the first series of experiments, the size of specimens, $24''\times\frac{5}{8}''\times\frac{3}{8}''$, was chosen to fit the apparatus used for determining Young's modulus by bending. The specimens were all made the same size by planing mill machinery. The dimensions were measured with micrometer calipers and the weights determined with a sensitive analytical balance.

The physical properties measured are closely related to the (physical) constant factors which appear in the differential equation of motion for a bar clamped at one end with the other end free to vibrate. A statement of this equation is

$$md^2y/dt^2+rdy/dt+sy=0,$$

where m is the apparent mass of the bar which is considered as vibrating at the free end and having the same kinetic energy as the whole bar, r is the resistance to motion per unit velocity of the free end, and s is the elastic restoring force per unit displacement y at the free end.

The values of m, r and s are known from the following relations and measurements. The displacement y at the free end when a force F is applied perpendicular to the axis of the bar is given by the relation $y=L^3F/3EI$, where L is the length of the bar, E is Young's modulus of elasticity and I is the moment of inertia of the cross section of the bar. The value of s is given by the relation $s=F/y=3EI/L^3$. The value of effective mass m is given by the relation $m=M/4.121$ where M is the mass of the total vibrating bar.* The constant r may be considered as the sum of two parts, one the internal and the other the external resistance to motion. The total resistance r was found by the relation $r=2m\rho f$,* where f is the natural frequency of vibration, m is the apparent mass and ρ is the logarithmic decrement.† The external resistance r_2 was found by the relation

$$r_2=2\pi m(f_2-f_1),^*$$

where f_1 and f_2 are the frequencies of the vibrating rod corresponding to energies one-half of that at resonance. In finding r_2 the rod was pivoted at one end, encountering only external resistance, and made to vibrate with simple harmonic motion in a horizontal plane by means of a very weak spring whose resistance was negligible. The internal resistance r_1 of the rod is given by the relation $r_1=r-r_2$.

TABLE I.

	DYNES PER CM PER SEC. r_1	G PER CC D	DYNES PER SQ. CM E
Spruce	12	0.50	1.44×10^{11}
Curly maple	9	0.56	0.58
Yellow poplar	10	0.55	1.27
White Pine	12	0.50	1.20
Fir	26	0.51	1.64
Cypress	32	0.62	1.90
Sycamore	18	0.56	0.56
Cotton wood	27	0.52	1.45
Bass wood	23	0.44	1.29

* The theoretical development of this relation from the equation of motion given above is too long to be given here.

† The log decrement was found from ratios of successive amplitudes as the natural vibrations were damped out.

The density D, internal resistance r_1 and Young's modulus E were measured for ten or more specimens from samples of each variety of wood tested and average values were computed. Table I gives these average values.

The values found for the resistance depend upon the shape and size of the specimens; however, since the specimens were all geometrically alike the values are relative and can be used for comparison.

TABLE II.

AVERAGE VALUES FOR SPRUCE	ACCEPTED	REJECTED
Density D, grams per cc	0.442	0.438
Elasticity E_1, dynes per sq. cm (Young's mod. with grain)	10.98×10^{10}	10.22×10^{10}
Elasticity E_2, dynes per sq. cm (Young's mod. against grain)	3.33×10^{9}	2.96×10^{9}
Hysteresis L, percent energy lost per cycle	6.36	6.20
Conductivity K, mhos across one-cm cube	3.85×10^{-13}	2.68×10^{-13}

Measurements were made which show that resistance as well as other properties vary with change of temperature, that changes in relative humidity affect principally the density of wood, and that Young's modulus apparently is little affected by paints, stains and varnishes.

In the design of musical instruments, such as violins, pianos, etc., it appears from the above results that much attention should be directed to testing the materials used in construction and to matching parts according to physical characteristics. The resulting instrument designed in this manner should show an improvement in tonal properties and frequency-response characteristics over ones not so designed.

In the second series of experiments, larger samples of the best spruce selected by a large piano manufacturing company for sounding boards, were tested. Twenty of these samples were marked rejected and 19 were considered acceptable material by the company. The samples were tested for the various physical properties without altering their size or shape. The methods and instruments used to make the tests need not be described here, but it may be said that they were not complicated or costly.

TABLE III. *Tabulated scores (39 spruce samples) arranged according to decreasing values.*

SCORES OF ACCEPTED SAMPLES	SCORES OF REJECTED SAMPLES	SCORES OF ACCEPTED SAMPLES	SCORES OF REJECTED SAMPLES
115		72	
105			71
105		68, 68	68, 68, 68
104		65	
100			64
98		62	62, 61
98		60	60, 59, 58
95		53	
94		50	
92			48
90	91, 83, 79, 78, 75, 73, 73		45
			29

The quantities measured were, Young's modulus E_1 with the grain and E_2 across the grain, density D, energy loss per half-cycle L, and electrical conductivity K. The average values for the acceptable wood are tabulated separately from those of the rejected wood to show trends favoring one class or the other. Just how the company separated the wood into the two classes is not clear; it is assumed that it was done by some subjective method.

If the trends shown in Table II hold for an increasing number of tested samples, one could standardize the various properties by using the average values given here to start with as standards and make adjustments as experience may require.

In this way, one might grade wood by giving a certain weight to each property value and adding up the total score. To illustrate this point, the values of certain properties were added together to get a score for each sample and then the scores were arranged according to decreasing values as given in Table III. It is to be noted that the 10 highest scores fall in the accepted column—this may not be an accident and needs more investigation.

Musical Theory in Retrospect

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Department of Scientific and Industrial Research, London, England

THERE were among the ancient Greeks, two of the most considerable sects of musicians: the Aristoxenians, and the Pythagoreans. They both agree thus far; that Diatesseron [a fourth] and Diapente [a fifth] do together make up Diapason [an octave]: . . . and the difference of these two, viz: of a fourth and a fifth, they agreed to call a tone; which is now called a whole note.

. . . . . .

Now, in order to this, Aristoxenus and his followers took that [i.e. difference] of a fourth, as a known interval, by the judgment of the ear; and, that of a fifth, likewise; and consequently, that of an octave, as the aggregate of both; and that of a tone, as the difference of those two.

And this of a tone, as a known interval, they took as a common measure, by which they estimated other intervals.

. . . . . .

Pythagoras, and those who follow him, not taking the ear alone to be a competent judge in a case so nice, chose to distinguish these, not by intervals, but by proportions.

. . . . . .

The two eminent sects among the ancients, the Aristoxenian and the Pythagorean, differ much in the same way as the language of our ordinary practical musicians, and that of those who treat of it in a more speculative way.

. . . . . .

And though our present gamut takes no notice of this little diversity, yet, in vocal music, the ear directs the voice to a more just proportion.— PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY VOL. XX; (1698). "On the Imperfections in an Organ"; Dr. Wallis, F.R.S.

This pronouncement by Dr. Wallis, and particularly its last two paragraphs, is as apposite today, and as significant, as it was when he made it, nearly 250 years ago. Those of us who are content to think of music as something we hear will be equally content to be described as "ordinary practical musicians." We shall be glad to find ourselves carefully distinguished from the nineteenth-century Pythagoreans, who imagined that scales came first and music afterwards, and that music was something rooted in the harmonic series. These theorists appear to have lost sight of the fact that the harmonic series is only an arithmetical series which exhibits a succession of harmonic proportions; and what Archytas later called harmonic proportions were the ideal of the Pythagoreans. To them everything in nature was perfection and number. Music was a small-scale terrestrial example of a sublime mystery which, in a celestial dimension, was expressed in the harmony of the spheres. Pythagoras, about 550 B.C., had observed that when a vibrating string was halved in length its sound rose an octave [diapason]; when its length was reduced to two-thirds its sound rose a fifth [diapente]. Here the mystery became manifest; why should consonance be determined by the ratios of small whole numbers?

In the Annotations to his *Plaine and Easie Introduction to Practicall Musicke* (1597), we find Thomas Morley drawing the same distinction as Dr. Wallis drew a century later. "Musicke," he writes, "is either *speculative* or *practicall. Speculative is that kinde of musicke* which by Mathematical helpes, seeketh out the causes, properties, and natures of soundes by themselves, and compared with others proceeding no further, but content with the onlie contemplation of the Art. *Practical* is that which teacheth al that may be known in songs, eyther for the understanding of other men's, or making of one's own." And thirty years after Dr. Wallis' pronouncement we find Roger North, Attorney General to James II, expressing the "ordinary practical musician's" opinion of "speculative musicke" in his *Memoirs of Musicke* (1728):[1] "It is said of Pythagoras (Plut. *Archus. Irlandro Interprete*) that he dis-

[1] "First made known to the world, through the extracts given by Dr. Burney in the third volume of his 'General History of Music' ": Editor's preface to Roger North's book as published in 1846 by George Bell.

allowed the making a judgment of musick by the senses, but he would have it approved by the subtilety of the mind, and harmonicall proportion, and not by the faculty of hearing. *O Mirum!*"

Morley explains what was meant by harmonical proportion. In the Annotations to his book he writes: "Here be three numbers 6 4 3, whereof the first twoe are in *sesquialtera* habitude [3 : 2], and the latter two are in *sesquitertia* [4 : 3] . . . take the difference betwixt six and foure, which is two, and the difference of 4 and 3, which is 1, and compare the differences together, you shal find two to 1, as 6 is to 3, that is *dupla* habitude [2 : 1]. . . . Let there bee three lines taken for as many stringes or Organ-pipes, let the first be six foot long, the second foure, the thirde three; that of sixe will be a *diapason* or eight to that of three, and that of four will be *diapente* or fift above that of sixe."

The study of proportions, arithmetical, geometrical, and harmonical, was part of a course of mathematical instruction in those days. A treatise, in Latin, which bears on the title page a description of its contents beginning (with the author's name) "P. Petri Galtruchii Aurelianensis; Soc. Jesu *Mathematicae Totius*," published at Cambridge in 1668, apparently enjoyed a considerable reputation. It was in eight parts; and the last part, comprising eight chapters, is concerned with music. It shows us the "Mathematical helpes" on which Morley's "speculative musicke" depended. It deals with such matters as intervals, consonances, ratios, proportions, and modes; and it concludes with some paragraphs on the art of descant. It is interesting to observe that due importance is given to instruction in harmonic proportion. One piece of what mathematicians would describe as "bookwork" tells how to find the harmonic mean of two numbers, though by a somewhat cumbrous method. It is curious that the author did not use a simpler formula such as the schoolboy would use today, *viz.:* multiply the product of the numbers by 2 and divide the answer by their sum, a rule which Morley would have verified with the numbers 6 and 3, of which the harmonic mean is 4.

The writings quoted or referred to above appeared in the course of a hundred and thirty years; and before the end of that time the young science of acoustics had made up its mind about the natural basis of what we call harmonic overtones—so far, that is, as their origin is to be found in the vibrations of sounding bodies. These writings may suggest the background of musical theory against which we should view the discoveries that aroused the interest of Rameau (1683–1764). Even more instructive is the developing background of scientific thought from Morley's day to Rameau's. It is important to see these matters in their historical setting, both musical and scientific, if we are to understand why, after Rameau, musical theory should have returned to spend long years in the wilderness of uncertain speculation.

Throughout the middle ages men's understanding of nature was obscured by servility of thought, confusion of ideas, and mysticism. Aristotle's teaching was accepted as infallible. "Writers on science were merely commentators and never thought of bringing the statements of ancient authors to the test of experiment."[2] In no sphere of human thought did that remarkable period which we call the Renaissance give greater freedom to men's minds than it did in their ideas about the world they lived in. What had been a matter of dogma in medieval times became an experimental study of nature. Modern science came to birth.

One of the pioneers of the strict scientific method was William Gilbert (1544–1603), a Fellow of St. John's College, Cambridge, and physician to Queen Elizabeth, who wrote a book on magnetism which treated the subject experimentally.[3] Francis Bacon (1561–1626) gave impetus to the new movement by his writings, though he did no experimental work himself. Galileo (1564–1642) is one of the outstanding figures among the founders of experimental science. He shares with Mersenne (1588–1648) the discovery of the laws of vibrating strings, which tell us how the period of vibration of a string is determined by its length, its tension, and its density. It was only because Galileo had incurred the displeasure of the inquisition that Mersenne

[2] Florian Cajori, *History of Physics.*

[3] *De magneto, magneticisque corporibus, et de magno magnete tellure* (London, 1600). An English translation of this remarkable work was issued by the Gilbert Club of London in 1900.

was able, by his *Harmonie Universelle* (1636) to anticipate the publication of Galileo's results by two years. Mersenne did not establish the fact that a string vibrates as a whole, as two halves, three-thirds, and so on, and that it performs these several vibrations simultaneously; a fact which, more than 200 years later, helped to solve, at Helmholtz' hands, the problem set by Pythagoras—why is consonance determined by the ratios of small whole numbers? But Mersenne was acquainted with overtones. He reminds us that Aristotle had detected the octave overtone; and he records that a vibrating string gives out at least five sounds, which he identified as a fundamental and its octave, twelfth, fifteenth, and seventeenth. The observation is significant as showing that what came to be described, later, as harmonic overtones were the unaided discovery of the human ear.

Meanwhile, in England the new spirit of enquiry which had animated Gilbert's work had taken firm hold. It received the hall-mark of kingly favor when the Royal Society of London was incorporated by royal charter of King Charles II in 1662. The *Philosophical Transactions* of these early years, which record the communications of its Fellows and others, make fascinating reading, equally for the man of science and the layman; for they do not make use of an abstruse nomenclature such as must inevitably be used today when knowledge has made such far-reaching advances and become so specialized. We find men engaged in exploring a literally new world; experimenting, measuring, observing, and recording; and so establishing a vast body of data on which the edifice of modern science was to be built. Two papers, little known today outside specialist circles, are particularly significant for our present inquiry.

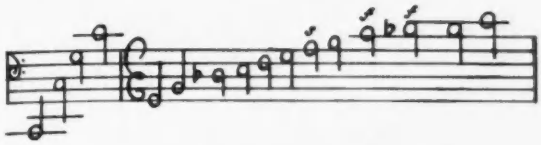
The first was communicated to the Society in 1677, under the title "On the Trembling of Consonant Strings, a new Musical Discovery," by Dr. Wallis from whose later paper, on the imperfections in an organ, quotations appear at the head of this article. John Wallis (1616–1703), English mathematician, went up to Emmanuel College, Cambridge, in 1632, became a Fellow of Queen's College, and was appointed Savilian Professor of Geometry in the University of Oxford in 1649—not the last Cambridge man to fill a chair of mathematics in the sister university. He held it till his death, 54 years later, in which time he made many notable contributions to mathematics. He was one of the original Fellows of the Royal Society. The paper with which we are now concerned is a milestone in the advance from Galileo and Mersenne.

Wallis begins by recording that sympathetic vibration at a unison (resonance) "has been long since observed." He goes on to describe a new musical discovery, first made three years earlier by Mr. William Noble, a Master of Arts of Merton College, concerning sympathetic vibrations in strings which were not in unison. First, he takes two strings, lying together and tuned an octave apart. When the one which gives the higher "note" is sounded, it excites the same "note" in the other string, which is found to be vibrating in two halves, for a paper rider at its midpoint is motionless. He then takes two strings tuned a twelfth apart. Sounding the one which gives the higher "note," he finds the other sounding in unison with it and vibrating in thirds, with two places (which we should call nodes) at which a paper rider is motionless. And so on. He gives observations on the confused sound produced by striking the string at a node, observations that were as searching as was possible in the existing state of knowledge. Here is a definite advance towards the physical explanation of harmonic overtones.

A passage with which Wallis ends his paper must be quoted for the picture it presents of the experimenter's attitude to a statement about nature which he has not verified. "I have heard also of a thin fine Venice glass cracked with the strong and lasting sound of a trumpet or cornet, near it, sounding an unison or a consonant note to that of the tone or ting of the glass. And I do not judge the thing very unlikely, though I have not had the opportunity of making the trial."

The second of our two papers was communicated in 1692 by Francis Robartes, who had been admitted Fellow of the Society in 1673. It is entitled "On the Defects and the Musical Notes of the Trumpet, and Trumpet Marine." The trumpet in question obviously had no keys and its tube was straight like that of Bach's trumpet. The notes would be similar to those of the modern bugle. The author begins by recording

that though the trumpet "has a large compass, the greater part of the intermediate notes are wanting, and some of them imperfect. The extent of this instrument cannot be strictly determined; it reaches as high as the strength of the breadth can force it." The author exhibits the observed notes in a musical stave, reproduced in Fig. 1 from the abridged edition of the *Transactions:*—"where the pricked notes are imperfect, not being exactly in tune, but a little flatter or sharper than the places where they stand, according as *f* or *s* is set over them." [The *f* which should belong to the lower *B*♭ was presumably omitted to avoid confusion with the lines of the stave.]



"Here we make two enquiries. 1. Whence it is, that the trumpet will perform no other notes in that compass besides those in the table, which are usually called by musicians trumpet notes. 2. What is the reason that the 7th, 11th, 13th, and 14th notes, are out of tune, and the others exactly in tune? In this matter we may receive some light from the trumpet marine"—clearly described as a monochord whose "notes" were excited by bowing and were selected by touching, not stopping, the string at points which divide it into aliquot parts. Today a violin player would call these harmonics. "If the strings be stopped in any part but such as produces a trumpet note, it yields a harsh and uncouth (not a musical) sound."

The author proceeds to examine these "notes" in the light of the familiar "trembling of consonant strings" described, fifteen years before, in Dr. Wallis' paper. He refers at this point to the "synchronous" vibrations excited, showing clearly that he was thinking in terms of the laws of vibrations of strings, which had been established for more than half a century— in other words, of the periods of vibration. This is important.

The author now calculates, by proportions, the lengths of the vibrating sections of the string required to give all the "trumpet notes" set out on the musical stave of his figure. By these lengths he shows that the intervals which we should call the harmonic seventh, eleventh, thirteenth, and fourteenth, "are out of tune, and the rest exactly in tune." The reader who wishes to be seized of his method of calculation may make trial with Morley's three strings whose lengths were 6, 4, and 3. Let us suppose that the notes of the first and last were *C* and its octave. The middle one, length 4, would then be *G*. *B*♭ a perfect fourth above *F* would be a major tone below the octave *C*. The length of string required to sound this *B*♭ would be found by multiplying 3 by the ratio of a major tone $\frac{8}{9}$, which gives a length $3\frac{3}{8}$. The length of string required for the harmonic seventh of *C* (ratio $\frac{1}{4}$) is given by the harmonic mean of 4 and 3. We have learnt how Morley would have calculated this, and the answer is $3\frac{3}{7}$. (We find the same answer if we multiply 6 by $\frac{1}{7}$.) This string is slightly longer than that sounding *B*♭ and therefore gives a flatter note. Some readers may recall that Helmholtz found *B*♭ to be a mutable note in the key of *C*.[4] To find the length of string which will sound a minor third (ratio $\frac{5}{6}$) above *G* we multiply 4 by $\frac{5}{6}$. The answer is $3\frac{1}{3}$, and this length is less than that of the two other strings, and this third string will therefore sound the highest note. It is the ear's demand for justly intoned intervals, in concords that form part of the prevailing harmony, which produces mutable notes; and it is mutable notes which require a flexible musical scale. The last of the quotations from Dr. Wallis which appear at the head of this article is significant.

These calculations of the lengths of strings are well worth making because they remind us, very clearly, that the "proportions" of the seventeenth-century theorists were concerned with tunings. The problem of tuning is essentially one of physical acoustics; it is tunings, not scales, that are rooted in arithmetic; and it was not the least of the misfortunes of the early nineteenth-century theorists that they confused the two.

To return to Robartes' paper, he continues: "Now to apply this to the trumpet, where the notes are produced only by the different force of the breath; it is reasonable to imagine that the

[4] *Tonempfindungen*, English translation, 1875, p. 423.

strongest blast raises the sound by breaking the air within the tube into the shortest vibrations, but that no musical sound will arise unless they are suited to some aliquot part, and so by reduplication exactly measure out the whole length of the instrument." And he concludes: "As a corollary to this discourse, we may observe that the distances of the trumpet notes, ascending continually, decreased in the proportion of 1/1 1/2 1/3 1/4 1/5 in infinitum." We may further observe that this series is the harmonic series of musical theory. It gives the relations between the *periods* of vibration of the notes shown in the figure. Any three successive terms are in Morley's "harmonical proportion."

These papers are particularly valuable for the light they throw on the derivation of "harmonic overtones" from the technical language of the seventeenth century. Robartes' use of the word "synchronous" shows, clearly, that he was thinking of the *periods* of vibration, which, as Galileo and Mersenne demonstrated, have precisely the same "proportions" as the lengths of the string to which they corresponded. How the ear could discover the proportions in the lengths of vibrating strings was a mystery in Morley's day. But when the discoveries of Galileo and Mersenne brought the time factor into the picture, and related the length of the string to its period of vibration, a great advance was made. It was not unreasonable to suppose that differing *periods* of vibrations which impinged on the ear drum would produce differences of sensation in the ear.[5] It remained to find out how the differences were perceived. These seventeenth-century men of science were getting very near the truth. But they had not yet found all the links in the chain that is needed to answer Pythagoras' question—why is consonance determined by the ratio of small whole numbers? In his *Tonempfindungen* (1862), Helmholtz returns to this enquiry, 170 years later. "To show what processes take place in the ear to render sensible the difference between consonance and dissonance, will be one of the principal problems in the second part of this work."[6]

Meanwhile men of an enquiring turn of mind who were interested in music continued to wonder about this mystery of nature. Lacking scientific evidence about their faculty of hearing, they turned to speculation. The first six and the eighth notes of the harmonic series, the "trumpet notes" shown in the figure, contained between them all the concords of academic counterpoint, and they were related, arithmetically, by a series of harmonic proportions. These proportions were "natural," for they were exhibited by the simple component vibrations which build up to produce the sound of a musical instrument. Therefore, they said, this *must* be the explanation of harmony, scales, key, and tonality; though they did not explain how our senses make us aware of the arithmetical relationships. Instead, the theorists just left the ear out of the picture; they assumed that, somehow, it gave a photographically accurate picture of the natural sounds in the air surrounding us; and they concentrated on what they called nature. They became, in the truest sense, neo-Pythagoreans, or "theoreticians," a felicitous title we owe to A. J. Ellis. He used this artificial term, quite guilelessly, in his translation of *Tonempfindungen*, for those musical theorists (*musikalischen Theoretikern*) against whom Helmholtz warned us because they were ready to embrace theories which their ears should have rejected.

Helnholtz makes an interesting comment on the evidence of harmony which Rameau found in "nature."[7]

> In the middle of the last [eighteenth] century, when much suffering arose from an artificial social condition, it might have been enough to show that a thing was *natural*, in order at the same time to prove that it must be *also* beautiful and desirable. . . . In nature we find not only beauty but ugliness, not only help but hurt. Hence the mere proof that anything is natural does not suffice to justify it esthetically. Moreover if Rameau had listened to the effects of striking rods, bells, and membranes, or blowing over hollow chambers, he might have heard many a perfectly dissonant chord, quite unlike those obtained from strings and musical instruments. And yet such chords cannot but be considered equally natural.

Since Helmholtz is here inviting attention to *inharmonic* overtones, we may recall the achievement of seventeenth-century bell-founders, such as those of the Netherlands, in so tuning bells

[5] The periodicity of the Harmonic Series is discussed, by Rayleigh in *Theory of Sound*, second edition, vol. I, p. 6.

[6] Reference 4, p. 24.

[7] Reference 4, p. 352.

as to get rid of their "natural" jangle. Moreover some of the higher harmonic overtones produce intervals which are not used in music, as was illustrated by Robartes' observations on the "trumpet notes" of the trumpet marine which he described as out of tune because they fell outside the musical gamut.

We must not be too hard on the nineteenth-century "theoretician." He was not wholly to blame for his musical misconceptions. It was because English musicians of the nineteenth century had forgotten their most glorious musical heritage, the music of the Tudor period, and because they accepted their counterpoint from Cherubini and their harmony from Dr. Day that English physicists and musicians, alike, were misled. On the other hand the physio-psychological science of hearing, which has given a new stimulus to musical acoustics, hardly came to birth before Helmholtz' time. Till then, the musical theorist looked in vain to science for an answer to the question set by Pythagoras, and for lack of guidance he began guessing. And nothing is more dangerous than to venture, without guiding hands, that of the musical scholar on the right, that of the man of science on the left, on "that untrodden wild" as Clerk Maxwell described it "between acoustics and music, that Serbonian bog where whole armies of scientific musicians and musical men of science have sunk without filling it up."[8]

A phrase that constantly tripped from the pen of the neo-Pythagorean was "the natural phenomenon of the harmonic series." We may invite the musician to consider its antitheses. "The natural phenomenon of an *inharmonic* series" is the response of the ear to inharmonic overtones such as those which produce the jangle of a bell. "An *unnatural* phenomenon of the harmonic series" would be the aural perception of some man whose ears were so different from ours that they would constantly distinguish the different overtones in a musical sound. The response of our ears to vowel sounds is a sufficient comment; both Helmholtz in *Tonempfindungen*[9] and Rayleigh in *Theory of Sound*[10] refer to an experiment, due to Ohm, which shows that the ear cannot help combining two *oo* sounds ($B\flat$) an octave apart, into the sound of *o* in *toad*. "The natural *phenomenon* of the harmonic series" means that when we listen to a complex vibration built up from a number of pendular vibrations whose periods are in harmonic proportion we hear a musical note. It has no other meaning; and the harmonic series of acoustics becomes a measuring rod which, applied to the elements of a complex vibration, enables us to say whether the listening ear will hear a musical sound or what Robartes called a "harsh and uncouth (not a musical) sound." We are indulging in what Bernard van Dieren called "romantic musing" if we expect anything else of it. And musicians will find that to learn all that men knew of harmonic proportion in the seventeenth century is well worth the labor involved, for it will enable them to realize this.

All of which brings us to the point of view of modern science, which attaches prime importance, in all acoustical studies, to the subjective response of the ear and the brain. Men of science and musicians meet on common ground today because the interest of both is in what we hear. The facts on which the speculations of the neo-Pythagoreans were based fall into the background, for as Helmholtz wrote in his *Physiological Optics:* "It may be said that the nature of a sensation depends primarily on the peculiar characteristics of the (receptor) nervous mechanism; the characteristics of the perceived object being only a secondary consideration." Helmholtz' attempt to build on the physiological basis which he discovered for the theory of music achieved less than he hoped for reasons indicated in a previous paper.[11] That is why the rebuilding of musical theory calls for cooperation between the musical scholar of today and the man of science. Some English musicians are aware of this, but it is largely from the pages of this journal that they are learning the scientific importance of distinguishing the sounds they hear from the vibrations they listen to. Perhaps, today, there is a particular appropriateness in a story which begins in England and leaves off in America.

[8] Rede Lecture, 1878.
[9] Reference 4, p. 102.
[10] Reference 5, p. 16.

[11] J. Acous. Soc. Am. **11**, 441 (1940).

Other English musicians are troubled by the disappearance of the old familiar landmarks. But, after all, these were only mirages, luring them to their doom in the Serbonian bog. The sensitive ear of the musician, and the practical expression of its properties which is embodied in music itself, are all that matter. The musician, the neo-Aristoxenian, now comes into his own. The "theoretician" who explained that composers had fallen into unscientific habits has long been suspected. When we find him, not "content with the onlie contemplation of the art," but disputing with musicians about it and teaching composers their business, we can turn today to science to discover why the "theoretician" was then invariably wrong.

Acoustical Society News

Why Not Attend the Acoustical Society Meetings?

OF the approximately 750 members of the Acoustical Society of America, about 150 attend the meetings regularly. If you are one of the absent 600, why not give some thought to the advantages of coming to the meetings? Of course you can read much of the technical material in the Journal, but papers do not usually appear in the Journal till three, six, or more months after they have been orally presented. Furthermore, progress reports on continuing investigations are often made at meetings, while publication may be delayed for years until the investigation is completed. But one of the most important advantages of attendance is the opportunity to meet the other members and to discuss their problems and yours informally. Many a man gets an offer of a new and better job because he is known personally to those members who are in position to employ men with interest and training in acoustics, and there are many unusual opportunities available at the moment.

There are often thrilling demonstrations of new acoustical devices at the meetings, and these must be heard to be fully appreciated; much is lost in merely reading the description of the device in the Journal. You really missed an exciting experience if you did not hear Harvey Fletcher *et al.* demonstrate the three-channel stereophonic recording system in the Eastman Theater at the Rochester meeting this spring; such naturalness, such quietness, such mighty volume. Another experience which I hope you did not miss was Homer Dudley's demonstration of the Vocoder at a previous meeting.

There are two meetings a year, spring and fall; the next meeting will be in New York at the Hotel Pennsylvania, October 24 and 25, 1941. The Society of Motion Picture Engineers meets here October 20–23, while the Optical Society of America and the Society of Rheology meet October 23–25, all in the same hotel. So why not come along and get some inspiration and new ideas, or in addition bring your wife for an acoustical vacation? And if you would like to present a paper at the meeting, you will find that the program committee is always worrying lest there should not be enough papers submitted, so let them have your abstract. You will soon receive a notice of the meeting and the address of the program committee.

Incidentally, are there not some other men in your organization who ought to be members of the Society? We would be glad to send them membership application blanks.—F. A. FIRESTONE.

Members Elected to Fellowship—May 6, 1941

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c/o Steinway & Sons
109 West 57th Street
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University of Illinois
Urbana, Illinois

Professor C. P. Boner
Department of Physics
University of Texas
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Harold Burris-Meyer
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William J. Sette
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Robert S. Shankland
Case School of Applied Science
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Music Department
Iowa City, Iowa

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Bell Telephone Laboratories
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S. N. Treviño
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Chicago, Illinois

C. F. Wiebusch
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Manager, Nederlandsche Western Electric n.v.
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James Ellison Shepherd
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Cambridge, Massachusetts

James Marion Snodgrass
Oscillograph Laboratory, Department of Psychology
Oberlin College
Oberlin, Ohio

Resigned: S. N. Kotwal
Charles Leigh
members

Dropped: Ely Rosenblum
S. E. Adair
John C. Bailey
L. E. Caldwell
V. Dubsky
Philip L. Freeman
A. M. Low
members

Fellows.....148
Members.....643

Total membership.....791

Current Publications on Acoustics

F. A. FIRESTONE

147 East Physics Building, University of Michigan, Ann Arbor, Michigan

Reviews of Contemporary Papers

MEMBERS who have occasion to translate important papers from foreign journals will be doing a real service to those members who do not read the foreign languages easily, if they will prepare a review of such articles for publication in this section.

These reviews should be of the nature of a lengthy abstract (500 to 1500 words) rather than a critique or appraisal, and should attempt to set forth in this limited space as much of the original author's contribution as possible. One or two figures may be included if desired.

Particular articles in French or German periodicals will be translated and reviewed in these columns by request. Address requests to Leo L. Beranek, Cruft Laboratory, Harvard University, Cambridge, Massachusetts.

Duration Thresholds for the Perception of Certain Transient Phenomena. W. TÜRK. Akustische Zeits. **5**, 129–145 (1940). The author points out the importance of knowledge of the perceptual aspects of transients, especially of the starting characteristics of speech and musical sounds. He reviews the previous work in the field from which deductions were made which determined the nature of the stimuli to be investigated in this study.

An apparatus was designed using mechanically controlled light intensity to operate a photoelectric cell, the output of which controls the amplitude of a constant frequency. The duration of stimuli can be controlled over the range 1.8 to 0.3 ms.[1] Figure 1 is a schematic diagram

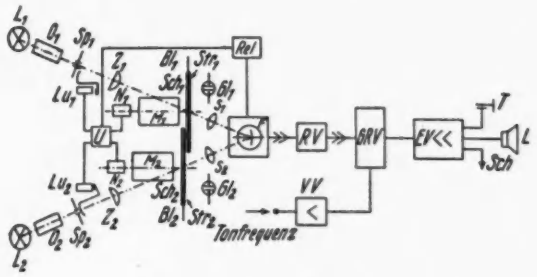

FIG. 1. Schematic diagram of the apparatus.

of the arrangement. A beam of light from an iron filament ballast lamp, L_1, L_2, passes through the lens, O_1, O_2, and strikes a 50-mm slit, Sp_1, Sp_2, which can be adjusted by means of a micrometer screw. The light passing the slit is focused at the point of interruption, Bl_1, Bl_2, by means of the cylindrical lens, Z_1, Z_2. Cardboard interruption patterns, Bl_1, Bl_2, are attached to a rotating aluminum disk, Sch_1, Sch_2, which is driven by a motor, M_1, M_2. These patterns control the light reaching the photoelectric cell, F, after passing the condenser lens, S_1, S_2. Figure 2 is a photograph of the apparatus.

The set-up has two independent optical systems and interruption disks in order to permit the presentation of comparison tones for psycho-physical purposes. Furthermore, an arrangement of relays which are kicked by the interruption patterns permits the selection of single impulses from the periodically recurring stimuli. For the presentation of comparison tones from the two optical systems an automatic switching arrangement is provided for, which presents the second tone at any desired interval after the first (see Fig. 1 Lu_1, Lu_2, U, and *Rel*).

Figure 3 is the wiring diagram of the apparatus including the relay system and Fig. 4 is an operating diagram of the relays. Reading the latter horizontally downward, the operation is as follows: (1) rest position, photo-cell cut out; (2) hand switch closed, photo-cell cut out; (3) point 1 runs up, relay *I* closes, photo-cell ready to operate; (4) interruption pattern controls output of photo-cell; (5) point 2 runs up, relay *II* closes, photo-cell cut out; (6) rest position, photo-cell cut out; (7) hand switch opened, relay *I* opens, relay *II* opens, photo-cell remains cut out; (8) as in 1 above.

It will be seen from Fig. 3 that the output of the photo-cell, which controls the amplitude of the oscillator, operates through a balanced circuit designed to eliminate the d.c. clicks. The click was inaudible when a tone was shut off.

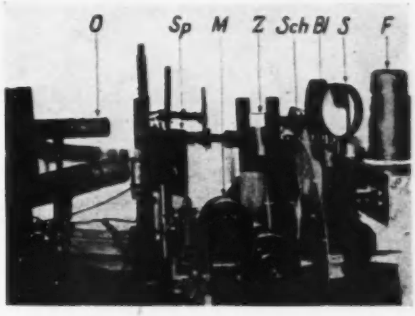

FIG. 2. *O*, lens mounting; *Sp*, adjustable slit; *Z*, cylindrical lens; *Sch*, rotating disk which carries interruption pattern; *M*, motor; *Bl*, interruption pattern; *S*, condenser lens; *F*, photoelectric cell.

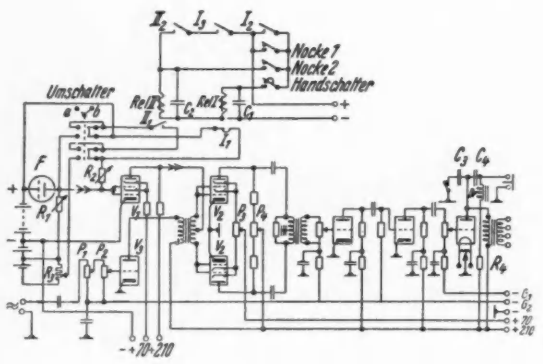

FIG. 3. Wiring diagram of the apparatus.

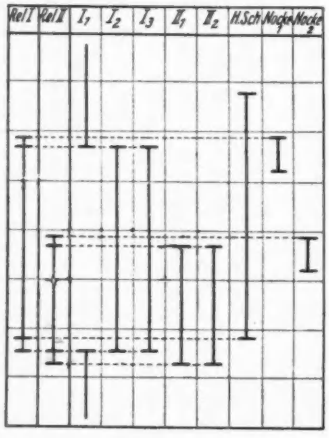

FIG. 4. Operating diagram of relay system.

Tests showed a linear relationship between the light intensity falling on the cell and the amplitude of the stimulus tone. Further, the over-all frequency characteristic of the system was practically flat from 25 to 18,000~. The output of the amplifier could be fed into a speaker, phone or oscillograph. The measurements described below were made with a high quality condenser headphone.

MEASUREMENTS

1. Duration thresholds for pitch perception

Bürck, Kotowski and Lichte[2] have shown that the pitch perception of short tones depends upon their energy spectrum. It is thus less a characteristic of the ear than of the stimulus. For the sake of comparison with the method used by them, their experiments were repeated using stimuli which started and stopped without a time constant. A typical envelope is shown in Fig. 7(b). Subjects were required to match the pitch of the short pulses with a pure tone and the pulse durations for proper recognition were determined. The results for three observers are shown in Fig. 5. Duration in ms on the ordinate is plotted against frequency on the abscissa.[3]

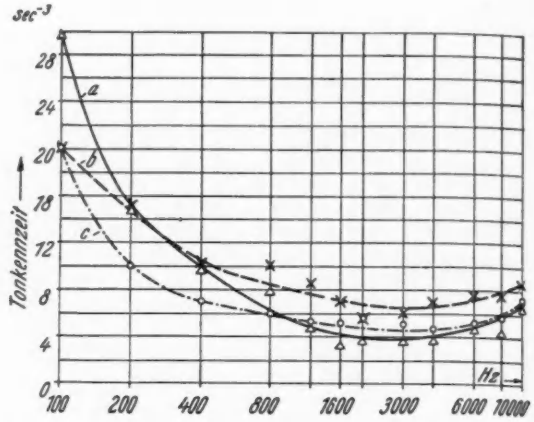

FIG. 5. Duration thresholds of pitch stability for three subjects observing tones with rectangular envelope.

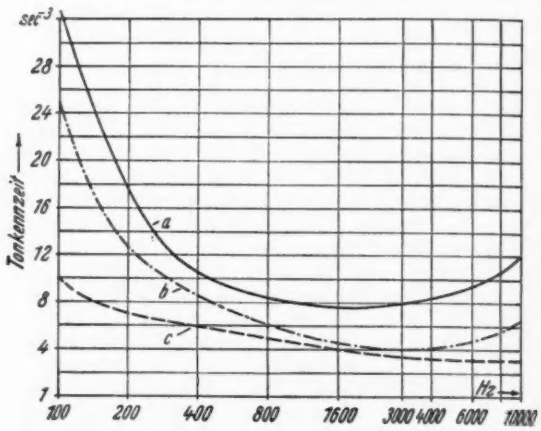

FIG. 6. Duration thresholds for pitch stability. Curve *a*, lowest threshold measured by Bürck, Kotowski and Lichte. Curve *b*, threshold using a rectangular stimulus envelope. Curve *c*, threshold using a rounded stimulus envelope.

Average values for this type of stimulus are shown in Fig. 6, curve *b*, together with the lowest threshold determined by Bürck, Kotowski and Lichte for the same type of stimulus produced by a different method, curve *a*. These two curves for the same kind of stimuli agree in form, but that of Bürck, Kotowski and Lichte is higher, probably due to the greater amount of click in their stimuli. The author's observers reported that for pulses of longer duration they could easily differentiate tone and click. But as the pulses were shortened perception of pitch became weaker and the click louder until at the threshold the effect was one of the click masking out the pitch of the tone.

If pitch perception is chiefly a function of the frequency spectrum, it would be expected that a reduction of the side-bands in the spectrum would cause a lowering of the threshold. This kind of spectrum can be attained by using a stimulus having a time constant at the start and end. Threshold measurements were made using stimuli of the form shown in (c), Fig. 7. The average threshold is shown

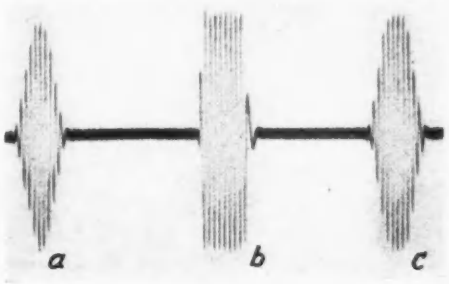

FIG. 7. (a) Sinusoidal envelope, (b) rectangular envelope, (c) rounded envelope.

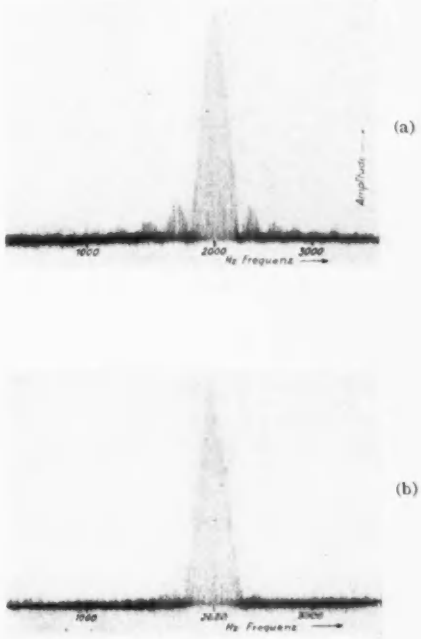

FIG. 8. Frequency spectrum analyses of 2000 ~ pulses of 4 ms duration. (a) Pulse with rectangular envelope; (b) pulse with rounded envelope.

in curve *c* of Fig. 6. In the middle range, curve *c* is not much below curve *b*, but at the low and high frequencies its values are only half those of curve *b*.

If one compares short pulses of the same frequency with rectangular and rounded envelopes near the duration threshold, it is found that the pitch of those with the rectangular envelope is sharp of those with the rounded envelope at low frequencies and flat of them at high frequencies. In the middle range the pitches are about the same. This fact can be explained on the basis of the wider side band of the spectrum of pulses with the rectangular envelope. At low frequencies the ear is less sensitive to the partials below the nominal frequency and more sensitive to those above it. Since for these short pulses the frequency spectrum is nearly symmetrical there is a perceptual shifting of the mode of the spectrum toward a higher pitch. The reverse is true at the high frequencies. When the duration of the pulse becomes too short, the frequency spectrum becomes so wide that the ear cannot resolve the pitch.

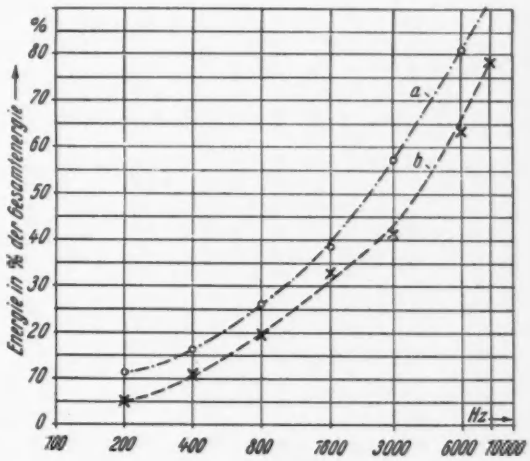

FIG. 9. Proportion of the total energy in a band ±2 percent around the nominal frequency in the pulses of the threshold curves *b* and *c* of Fig. 6. Curve *a* for pulses with rectangular envelope. Curve *b* for pulses with rounded envelope.

In order to make a qualitative evaluation of the stimuli, all of the pulses which were used in the determination of curves *b* and *c* of Fig. 6 were analyzed for frequency spectrum by means of the Weymann automatic analyzer.[4] Typical analyses are shown in Fig. 8(a), (b). As would be expected, the band spread is greater for the pulse with rectangular envelope than that with the rounded envelope. Both of these pulses were 4 ms in duration. In accordance with the procedure adopted in Bürck, Kotowski and Lichte, the percent of energy in a band ±2 percent around the nominal frequency was computed for all the spectra. The values are shown in Fig. 9. Curve *a* is for pulses with rectangular envelope and curve *b* for those with rounded envelope. It will be seen that at 200~ the rectangular pulse requires 11 percent of the energy in the band ±2 percent of the nominal frequency for proper recognition of pitch, as against 6 percent for the rounded pulse, while at 8000~ the percent is 93 as against 78. These results show that the assumption of Bürck, Kotowski and Lichte that the important energy for the recognition of the pitch of short pulses lies in a band ±2 percent of the nominal frequency does not fit the facts. Actually in each case this band must be dependent upon the differential pitch sensitivity. Consequently, differential thresholds in terms of the percent increment of the frequency necessary to give rise to a least perceptible pitch difference at the duration thresholds were determined using both rectangular and rounded pulses. The results are shown in Fig. 10. Δf in percent is plotted on the ordinate against f on the abscissa. Curve *a* is for rectangular envelopes and curve *b* for rounded envelopes. The trend of these curves is about the same as that for prolonged tones, but the latter show smaller values throughout.

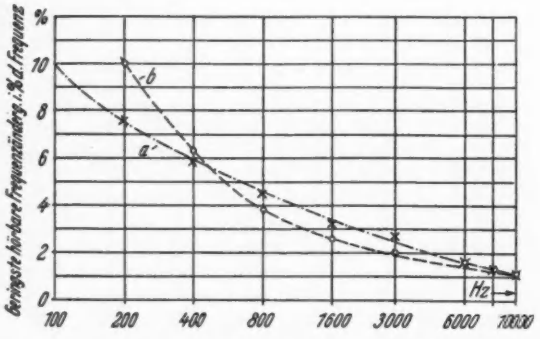

FIG. 10. Differential pitch sensitivity at the duration thresholds for pitch stability. Curve *a*, with pulses of rectangular envelope. Curve *b*, with pulses of rounded envelope.

If, now, the percent of energy in a band corresponding in width to the magnitude of Δf in percent at each frequency is computed, more satisfactory results are obtained than those shown in Fig. 9. These are given in Fig. 11. It will be noted that, at the duration threshold for pitch stability, the proportion of the total energy necessary for pitch recognition at 200~ is 41 percent for rectangular envelopes and 30 percent for rounded envelopes. At 8000~ the percentages are 78.5 and 53, respectively.

In the light of the information shown in Fig. 11, the author discusses the equation advanced by Bürck, Kotowski and Lichte for computing duration thresholds for pitch stability. After introducing certain corrections he gives the equation:

$$T = (2 \cdot n)^1 / p \cdot f,$$

where T is the duration threshold, p is Δf in terms of percent, n the percentage of energy in a band of the width of Δf around the nominal frequency, and f the nominal frequency. Using this equation, the computed values were in practically perfect agreement with measured values for both rectangular envelopes and rounded envelopes. This is shown in Fig. 12.

2. The physiological building-up process

Von Békésy and Bürck, Kotowski and Lichte have outlined a method for defining the transient response of the ear. A tone which reaches maximum amplitude instantaneously is followed by one which has a time constant in the build-up. The time constant is reduced until an observer is unable to differentiate between the two stimuli. This threshold represents the transient response of the ear. The author made measurements using stimuli of the type shown in Fig. 13. The first stimulus reached maximum amplitude in 0.05 ms. The comparison stimulus had an exponential starting characteristic. Both stimuli were held at maximum amplitude for 35 ms and then stopped linearly in 20 ms. The gradual stopping eliminated click which would have reduced the ability to differentiate the starting characteristics. When the comparison tone had a time constant of 0.5 ms all observers were able to differentiate the two starting characteristics. The difference was most pronounced in the region 50–800~. It was less apparent from 1200–5000~ and then became more pro-

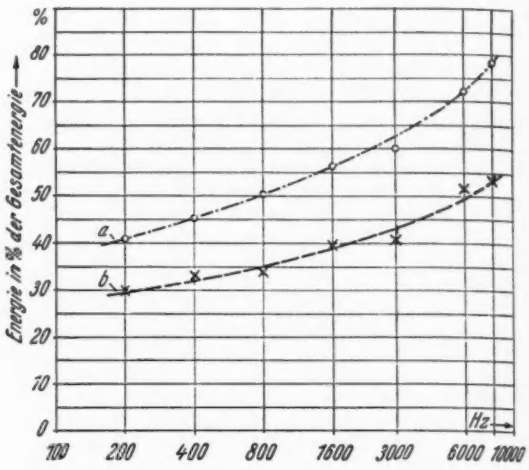

FIG. 11. Proportion of the total energy within a band around the nominal frequency determined by Δf (in percent) at each frequency. Each tone at the duration threshold for pitch stability (Fig. 6). (a) Rectangular envelopes; (b) rounded envelopes.

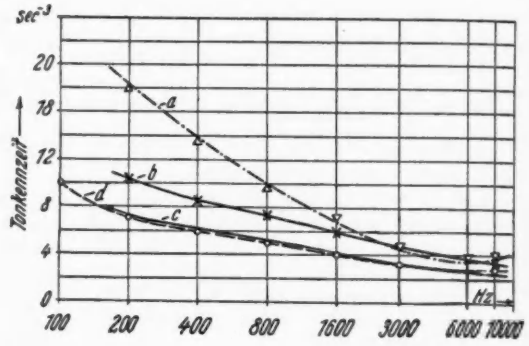

FIG. 12. Duration thresholds for pitch stability using pulses with rounded envelopes. (a) Computed for $p = 2$ percent and n values from Fig. 9 (curve *b*); (b) computed for p values from Fig. 10 (curve *b*) and n values from Fig. 11 (curve *b*); (c) the same as *b*, but divided by $\sqrt{2}$; (d) measured values.

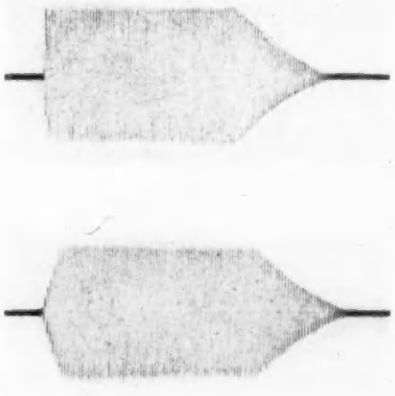

FIG. 13. Oscillograms of comparison tones used for the determination of the transient response of the ear.

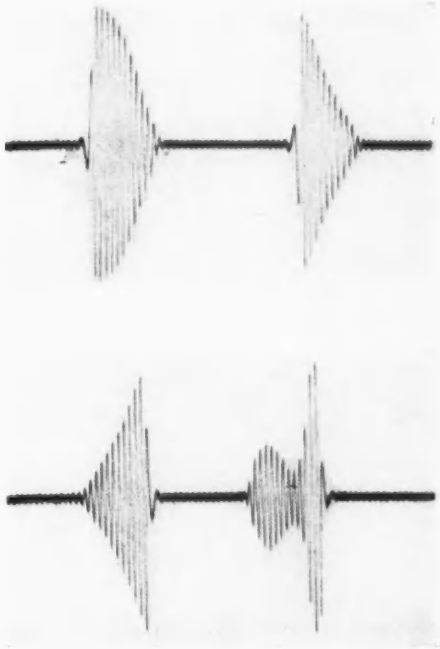

FIG. 14. Oscillograms of stimuli to be compared in order to determine the sensitivity of the ear to pulses of the same duration but different envelope.

nounced from 6000∼ upward. When the starting characteristic of the comparison tone was reduced to 0.25 ms the two stimuli could still be differentiated at the high and low frequencies, but in the region of 3000∼ the difference between them disappeared. In order to reduce the masking effect which the constant middle portion of the stimuli might have on the discrimination, this was removed so that the stopping characteristic began immediately after maximum amplitude of the starting characteristic was reached. Under these conditions, the comparison stimulus with a starting time constant of 0.25 ms could be differentiated from the standard stimulus at all frequencies. Since the accuracy of the apparatus would not permit a further reduction of the time constant of the starting characteristic it was impossible to establish the curve for the transient response of the ear. It is to be noted, however, that at all frequencies from 50 to 10,000∼ these values will be smaller than 0.25 ms.

3. Limits in the ability to differentiate stimuli with various envelopes

After it had been shown that the ear is very sensitive to starting characteristics of different durations, experiments were made to determine whether starting characteristics of the same duration but of different form can likewise be differentiated. The procedure was to compare stimuli of the same duration, such as those shown in Fig. 14, and, maintaining the form of the envelope, gradually to reduce the duration of both stimuli by the same amount until there was no perceptual difference between them. One experimental series consisted of stimuli which had starting

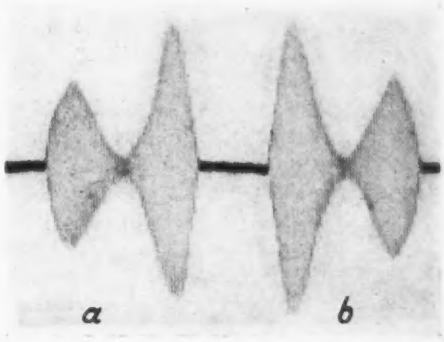

FIG. 15. Oscillogram of mirror image comparison stimuli.

characteristics of different forms and which were cut off without a time constant upon reaching maximum amplitude. In another series the same starting characteristics were then used with a stopping characteristic five times the duration of the start. In both series all pairs of stimuli could be differentiated at 2 ms duration over the range 100 to 10,000∼. The differentiation was more noticeable with periodic repetition than with a single presentation.

These experiments showed clearly that the differentiation is of two different kinds. With relatively long starting characteristics, down to about 10 ms, the audible difference depends upon the difference in envelope. The different growths in amplitude are perceived directly. Differences in the tone quality of the start are hardly noticed. Then there is a transitional stage in which both the growth of the envelope and the clang are noticed. Below this, the differentiation seems to be due solely to differences in the tone quality of the stimuli.

In order to determine whether the differences of very short stimuli are due only to the entire frequency spectrum

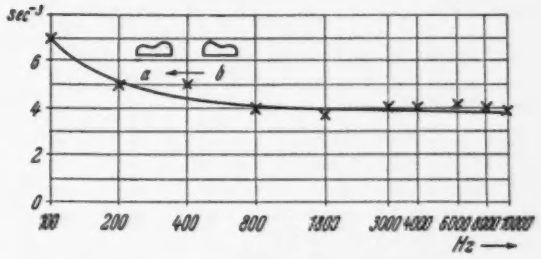

FIG. 16. Threshold for differentiation of the stimuli shown in Fig. 15.

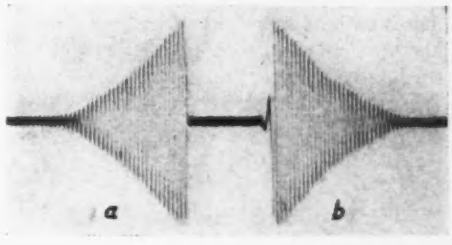

FIG. 17. Oscillogram of comparison tones.

or whether the temporal course of the stimulus is perceived, stimuli of mirror image such as those shown in Fig. 15 were used. These could be differentiated down to the durations given in Fig. 16.

When stimuli such as those shown in Fig. 17 were used they could be perceptually differentiated at all frequencies from 100 to 10,000~ down to 1 ms duration. Although the frequency spectrum of these two stimuli considered as a whole is the same, stimulus *a* gives the auditory impression of being "softer" than stimulus *b* at all frequencies. Stimulus *b* is perceived as "sharp" in contrast to stimulus *a*. This fact can be explained by assuming that, with the constantly increasing start, the tone and its neighboring frequencies have more perceptual weight than the click at the end of the stimulus for which the sensitivity of the ear is diminished by the preceding portion of the stimulus. With stimulus *b*, on the other hand, the initial click is perceptually more prominent than the remainder of the stimulus. The problem is raised whether this is a fatigue or masking effect.

J. M. COWAN
State University of Iowa

[1] *Reviewer's note:* In all studies of stimuli of very short duration it is of crucial importance to know where the durations are measured. The author makes it clear that he made duration measurements across the input to the high quality condenser headphone which was used for the experiments. If measurements of the durations of the actual stimuli in the air were made, this is not mentioned in the text.

[2] W. Bürck, P. Kotowski and H. Lichte, "Der Aufbau des Tonhöhenbewusstseins," E. N. T. **12**, 326 (1935).

[3] *Reviewer's note:* The threshold thus defined will hereafter be referred to as the duration threshold for pitch stability, or simply duration threshold. It is that duration beyond which increased duration does not significantly affect the pitch.

[4] G. Weymann, "Ueber den Aufbau von Suchtonanalysatoren," Hochfrequenztech. **49**, 181 (1937).

Book Reviews

The Voice, Its Production and Reproduction. DOUGLAS STANLEY AND J. P. MAXFIELD. Pp. 262, Figs. 32. Pitman Publishing Company, New York. Price $2.50.

Maxfield is responsible for the physics. He has been able to simplify his presentation enough so that the average voice teacher can follow it with ease. And his choice of material is such as to be of more than usual value to them. One leaves this part of the book with regret that it covers only 32 of its 262 pages. He gives a very simple and readily understood explanation of such terms as decibel, reverberation, vibrato, and others which might well puzzle the average teacher and student of voice. Yet their vital importance must be apparent to all. And his lucid explanation will undoubtedly be appreciated.

Stanley, in turn, strikes out rather vigorously against the manifest confusion in the minds of these teachers and students insofar as the nature of sound itself is concerned. He is sharply critical of the many books on voice. And he makes it clear that he feels their authors, as well as the teachers and students of voice, should have a better knowledge of the scientific facts, as they pertain to the subject.

He has been in close touch with a large number of outstanding physicists, such as Maxfield, for a number of years now. And that aspect of the book's presentation undoubtedly represents a sound, scientific contribution. Indeed, one often wishes that he had confined himself thereto.

His knowledge of the physiology involved leaves much to be desired. In consequence his discussion is often confused and verbose; in other words, he is guilty of exactly the same sins he condemns so vigorously in others. One quotation used by another reviewer will suffice to demonstrate that fact. Stanley says:

> "If the concept is clearly defined and no inhibition is present, and if the mouth cavity is shaped against the mouth vowel position, it must follow that the extensor muscles of the laryngeal pharynx will come into tension."

How can the mouth cavity be shaped against the mouth vowel position? Any individual who knows his physiology realizes that the mouth cavity is the mouth vowel position. And his usage of the expression "extensor muscles of the laryngeal pharynx" leaves us all scrambling to know what he means. What are they? Why involve them here? And just why should they come into tension, under the conditions he indicates? Furthermore, is it not making a very unscientific assumption for one to say that if the concept is clearly defined and no inhibition is present, the manifestations he indicates must inevitably follow? We say he makes the assumption for he adduces no proof. In fact, a large part of his 230 pages is made up of observations of this kind without citation of proof to verify them.

He develops a strange and unproved concept in regard to the falsetto. Again his physiology is open to serious question. Yet much of his teaching approach is made dependent on it. But he is not unique in that respect. Most authors who would be scientists, yet assume to wander off into the field which is legitimately that of the voice teacher, shortly find themselves guilty of riding pseudo-scientific hobbies. Many have undoubtedly wished that Muckey, Holbrook, or Miller, for example, had stayed with their medical practice instead of attempting to tell the voice teacher how to teach, or even go off into voice teaching

themselves. The result is almost invariably what the profession calls a "theory." But they are not theories at all. They are not even hypotheses. They are rather empirical methods based upon one man's concept or series of ideas. Hence, all that such a scientist does is add another teaching method to the innumerable ones already in vogue. And what scientific facts he utilizes are only to serve as better sales talk for his slight deviations in method of approach, or to give him the edge on other teachers.

Yet undoubtedly Stanley has made the profession give more careful thought to the actual facts involved in voice production. And be more critical of unsupported, subjective impressions. He has brought them back rather sharply to the necessity of giving more careful attention to the vibrato, for example. There might be justifiable difference of opinion as to his method of utilizing the facts now known concerning this voice manifestation. And he unfortunately gives no credit to the fine scientists who have worked on this subject, such as Max Schoen, Carl Seashore and his students. But he should have credit for arousing the voice-teaching profession and making them aware of its importance.

Probably no books in the field of science have aroused more comment or had more influence on both voice teachers and students from the scientific standpoint. And Stanley's books, while of no such high scientific standard as D. C. Miller's *Science of Musical Sounds*, will undoubtedly be found on the shelves of teachers of voice for some time to come.

G. Oscar Russell
Ohio State University

Acoustics. Alexander Wood. Pp. 575. Interscience Publishers, New York, 1941. Price $6.00.

This book entitled *Acoustics* by Alexander Wood is not to be confused with the *Textbook of Sound* by A. B. Wood. The author is Fellow and Tutor of Emmanuel College, Cambridge and University Lecturer in Experimental Physics. In the preface, he makes the following statement: "The book has been written primarily for the interest of writing it, and I trust that some of my own interest may have communicated itself to the printed page." This is indeed an unusually interesting textbook; in fact, this reviewer tried to leaf through it hastily in order to determine the subject matter covered, but said hasty leafing required several evenings, not only because the book is long and covers a wide range of subjects, but also because of the fascinating manner in which unfamiliar historical material and unusual experimental material have been interwoven with the customary mathematical treatment. The book is a synthesis of Lamb, Barton, Miller, Fletcher, Bergmann, and Watson, all brought up to date.

In addition to the dynamical theory of vibrating systems and wave motion, there is much material on supersonics, underwater sound, speech, hearing, and architectural acoustics. This would be a worthy text for an extended course in Sound at either the intermediate or advanced level; it would also be useful as a reference on account of the wide variety of subject matter.

This book is a valuable contribution.

F. A. Firestone
University of Michigan

References to Contemporary Papers on Acoustics

MOST of the titles of papers appearing in other languages than English have been translated. Abstracts in English of many foreign papers have appeared or soon will appear in Science Abstracts, Section A. Where references are made to Science Abstracts, the reference is to the volume number and abstract number. The abbreviations of the names of journals are those used in Science Abstracts and can be found in any annual index to those abstracts.

The numbers appearing at the head of each entry are the numbers which identify the subject headings in the Cumulative Index of this journal issued in November, 1939. This same Classification of Subjects can be found in the index to Volume 12.

Compiled with the generous assistance of Samuel Sass, Physics Librarian, University of Michigan.

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5.16 **A New Film Gramophone.** E. J. Wender. Wireless World **47**, 47 (Feb. 1941).

5.16 **Sound in Motion Pictures—II.** Nathan Levinson. Electronics **14**, 37–39, 88 (Feb. 1941).

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6.5 **Klangspektren einer Silbermannorgel. (The Tone Spectrum of a Silbermann Organ.)** W. Lottermoser. Akustische Zeits. **5**, 324–325, 330 (Dec. 1940).

6.6 **Konzertmäkige Zweikanal-Schallübertragung für das Cembalo. (Two Channel Concert Amplifier for the Cembalo.)** Erich Thienhaus. Akustische Zeits. **6**, 34–45 (Jan. 1941).

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7.1 **Less Noise, Fewer Errors.** N. D. Stone. Bankers Monthly **58**, 8–9 (Jan. 1941).

7.7 **Problems of the Singing Propeller.** W. Kerr, J. F. Shannon and R. N. Arnold. Inst. Mech. Eng. Proc., London **144**, 54–76; disc., 76–90 (Dec. 1940). Sci. Abs. **A44**, 25 (1941).

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10.3 **An Optical Method for the Measurement of Ultrasonic Absorption.** E. C. Gregg, Jr., Rev. Sci. Instruments **12**, 149–151 (March, 1941).

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10.5 **New Technique for Determining Ultrasonic Velocities in Liquids.** R. L. Narasimhaiya and C. S. Doraiswami. Indian Journ. Phys. **14**, 187–189 (June, 1940). Sci. Abs. **A44**, 130 (1941).

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10.7 **Theory of Acoustical Double Refraction of Colloidal Liquids.** Zeits. f. Physik **116**, 632–651 (Nov. 21, 1940).

10.8 **Depolymerization of Macromolecules by Supersonic Waves.** G. Schmid. Phys. Zeits. **41**, 326–337 (July 1 and 15, 1940).

10.8 **Effect of the Application of Sonic Energy to the Hydrolysis of Potassium Persulfate.** W. C. Schumb and E. S. Rittner. Am. Chem. Soc., J. **62**, 3416–3420 (Dec. 1940).

10.9 **The Extraction of Antigens by Sound Waves.** Science (Supplement) **93**, 10 (Feb. 21, 1941).

11. Waves and Vibrations

11.2 **Acoustic Refraction and Total Reflection.** A. Schmidt and A. Kling. Phys. Zeits. **41**, 407–409 (Sept. 1 and 15, 1940).

11.3 **A Determination of the Elastic Modulus S of Beta-Quartz.** A. W. Lawson. Phys. Rev. **59**, 608–612 (April 1, 1941).

11.3 **Dependence of the Velocity of Sound on the Concentration in a Dipole-Nondipole Fluid Mixture.** K. Sacher. Phys. Zeits. **41**, 360–362 (Aug. 1, 1940).

11.3 **Ein Material sehr hoher Schallgeschwindigkeit. (A Material of Very High Sound Velocity.)** Heinz Thiede. Akustische Zeits. **6**, 64 (Jan. 1941).

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11.5 **Energy Considerations in Sound Radiation Pressure.** F. BOPP. Ann. d. Physik **38**, 495–500 (Oct. 29, 1940).

11.5 **The Air-Jet with a Velocity Exceeding that of Sound.** JUL. HARTMANN AND FREIMUT LAZARUS. Phil. Mag. **31**, 35–50 (Jan. 1941).

11.6 **Experimentelle Untersuchungen zur Theorie der Schallaus-Breitung in Schalldämpfenden Rohren. (Experimental Researches in the Theory of Sound Propagation in Absorbing Tubes.)** WERNER LIPPERT. Akustische Zeits. **6**, 46–64 (Jan. 1941).

11.7 **Energy Considerations in Sound Radiation Pressure.** F. BOPP. Ann. d. Physik **38**, 495–500 (Oct. 29, 1940).

11.7 **The Air-Jet with a Velocity Exceeding that of Sound.** JUL. HARTMANN AND FREIMUT LAZARUS. Phil. Mag. **31**, 35–50 (Jan. 1941).

11.7 **Book Review: Practical Solution of Torsional Vibration Problems. Vol. 1 (Second edition).** W. KER WILSON. Chapman and Hall, Ltd., London, Reviewed in Journ. Sci. Instruments **18**, 15 (Jan. 1941).

11.7 **The Velocity of Longitudinal Waves in Cylindrical Bars.** DENNISON BANCROFT. Phys. Rev. **59**, 588–593 (April 1, 1941).

11.7. **The Construction of Vector Diagrams for Damped Oscillations.** S. REISCH. Zeits. f. techn. Physik 21, 176–177 (1940).

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11.7 **Über Stationäre Strömungen in Kundtschen Rohr. (Stationary Waves in Kundt's Tube.)** K. SCHUSTER AND W. MATZ. Akustische Zeits. **5**, 349–352 (Dec. 1940).

11.7 **Some Experiments on Forced Vibrations of Varying Period.** K. SEZAWA AND W. WATANABE. Rep. Aero. Res. Inst. Tokyo, No. 195, 215–227 (Aug. 1940). Sci. Abs. **A44**, 27 (1941).

11.7 **Ein- und Zweidimensionale Ausbreitung von Wasserschall im Rohr-bzw, im Flachbecken. (One-and Two-Dimensional Radiation of Water Waves in Tubes, Especially Flat Dishes.)** KONRAD TAMM. Akustische Zeits. **6**, 16–34 (Jan. 1941).

11.7 **The Production of Waves by the Sudden Release of a Spherical Distribution of Compressed Air in the Atmosphere.** J. J. UNWIN. Roy. Soc., Proc. **A177**, 882 (Jan. 10, 1941).

11.7 **Vibrations of Free Plates: Isosceles Right-Angled Triangles.** M. D. WALLER. Phys. Soc., Proc. **53**, 35–39 (Jan. 1941).

11.7 **Negative Characteristics of the Vibrating Reed.** J. ZAHRADNICEK AND R. NESPOR. Phys. Zeits. **41**, 419–421 (Sept. 1 and 15, 1940).

11.7 **The Intrinsic Inelasticity of Large Plates.** CLARENCE ZENER. Phys. Rev. **59**, 669–673 (April 15, 1941).

Review of Acoustical Patents

HERBERT A. ERF
The H. A. Erf Acoustical Company, Cleveland, Ohio

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The decimal numbers appearing before each title are the numbers which identify the subject headings in the Cumulative Index of this journal issued in November, 1939. This same classification of subjects can be found in the index to Volume 12.

2,237,032

2.1 PROCESS OF INCREASING THE SOUND ABSORPTIVE PROPERTIES OF CELLULAR GLASS

Elmer H. Haux, assignor to Pittsburgh Plate Glass Company.

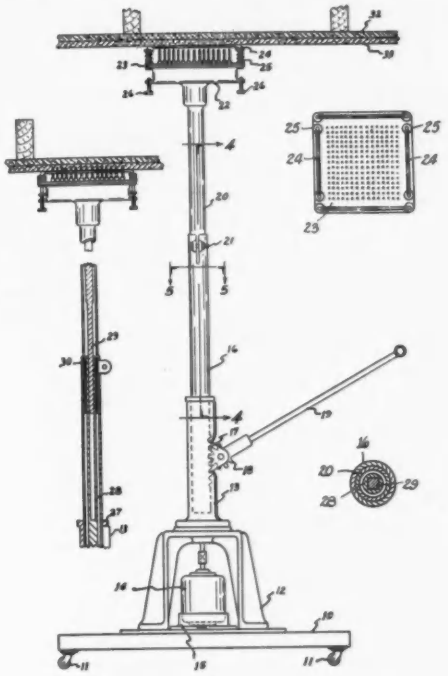
April 1, 1941, U.S.P.O. Cl. 49–89, 2 Claims.

The cellular glass is heated to approximately 300°F and then cooled rapidly to fracture a large percentage of the walls surrounding the individual compartments contained in the cellular structure to provide communicating channels between the cells.

2,234,789

2.1 ACOUSTICAL CORRECTION MACHINE

M. S. Wunderlich, assignor to The Insulite Company.
March 11, 1941, U.S.P.O. Cl. 144–110, 2 Claims.

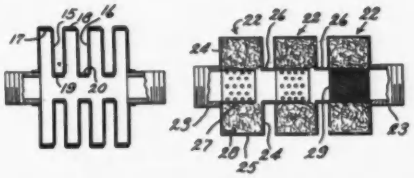


This invention is a drilling apparatus for perforating sound-absorbing material in place. The machine includes a drill head having a cover plate, a plurality of drills operatively mounted in the drill head and passing through the cover plate. A movable means is provided for feeding the drills into the work and also to limit the feeding and positioning of the drills.

2,233,804

2.9 FLUID SILENCER

Roland B. Bourne, assignor to The Maxim Silencer Company.
March 4, 1941, U.S.P.O. Cl. 181–50, 9 Claims.

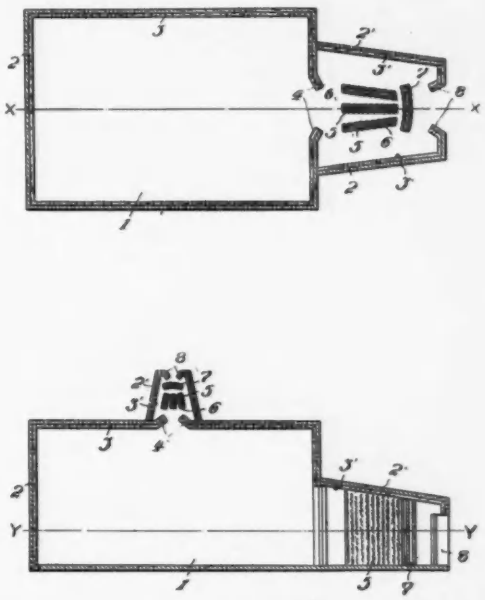


A sound-attenuating device for pipe-borne liquids comprising spaced conduit sections, a casing enclosing the space between the sections, and having plane end walls sufficiently flexible to prevent substantial transmission of sound through them. A baffle is interposed within the casing in the space between the sections.

2,233,966

2.2 SOUND ARRESTER AT THE OPENING OF SOUND-ARRESTING ROOM

Masaichi Tominaga, Kamata-ku, Tokyo, Japan.
March 4, 1941, U.S.P.O. Cl. 181–30, 3 Claims.



This invention related to a sound-insulating construction for the prevention of the emanation of sound from an enclosure. A funnel-shaped sound-absorbing housing or anteroom is constructed at the opening into the enclosure. The walls and ceiling are tapered, and baffles erected in the shape of a fan make up the sound-arresting structure.

2,239,688

2.9 SOUND-DEADENING COMPOSITION AND THE PROCESS OF PREPARING SAME

Paul G. Peik, assignor to Emulsions Process Corporation.
April 29, 1941, U.S.P.O. Cl. 134–1, 3 Claims.

Vibration insulation material for use in automobile bodies and the like.

2,240,014

2.9 SOUND DEADENER

Paul G. Peik, assignor to Emulsions Process Corporation.
April 29, 1941, U.S.P.O. Cl. 260–723, 6 Claims.

2,240,015

2.9 SOUND DEADENER

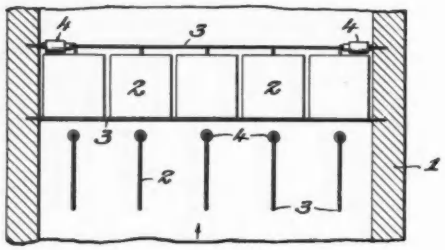
Paul G. Peik, assignor to Emulsions Process Corporation.
April 29, 1941, U.S.P.O. Cl. 260–723, 3 Claims.

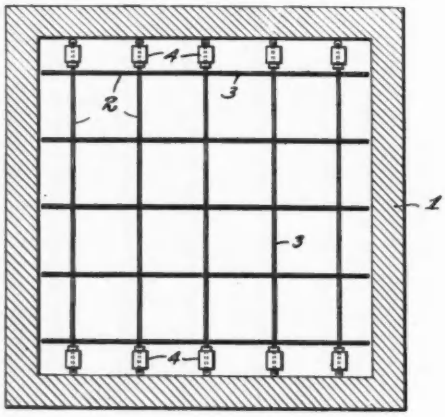
A sound-deadening composition comprising a non-colloidal water-in-oil emulsion of reclaimed rubber.

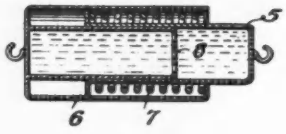
2,238,167

2.9 APPARATUS FOR PREVENTING OR DIMINISHING SOUND TRANSMISSION

Werner Genest, Berlin-Steglitz, Germany.
April 15, 1941, U.S.P.O. Cl. 181–46, 2 Claims.







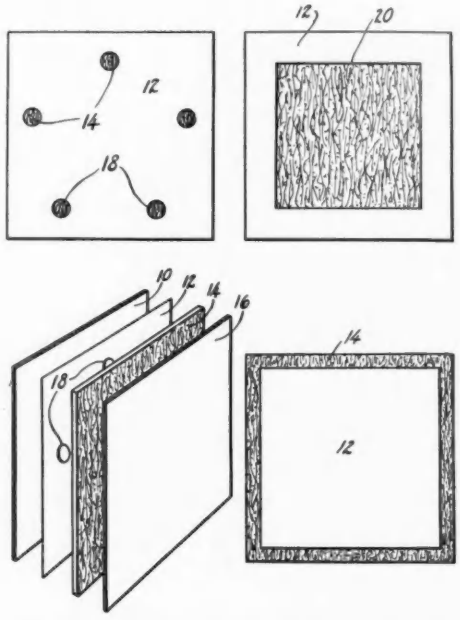
This patent covers a sound-absorbing apparatus for use in flues or shafts and consists of sound-absorbing plate elements attached to flexible supports arranged transversely of the flue or shaft and connected thereto by resilient means. The sound-absorbing elements are arranged parallel to the flow of air or gas in the flue or shaft.

2,240,326

2.9 LAMINATED INSULATION STRUCTURE

Earl A. Burns, assignor to Woodall Industries, Inc.
April 29, 1941, U.S.P.O. Cl. 154–44, 3 Claims.

This construction consists of a laminated panel comprising an inert vibration-damping material bound to a metal lamination using an asphaltic binder. A separator sheet is interposed between the metal lamination and the

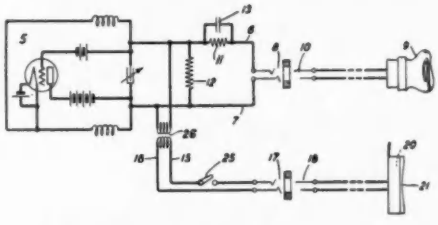


damping lamination, which separator sheet has small apertures to permit only a limited area of adhesion by the binder.

2,232,799

4.5 METHOD FOR TESTING BONE CONDUCTION

Harvey Fletcher, assignor to Bell Telephone Laboratories, Inc.
February 25, 1941, U.S.P.O. Cl. 128–2.1, 1 Claim.



The method of determining the bone conduction response in the hard of hearing which comprises applying by air conduction to the good ear of the patient a steady tone of given frequency and volume and by bone conduction to the osseous structure adjacent the poor ear, an interrupted tone of the same frequency but of lower volume, and noting the reaction of the patient to the interrupted tone.

2,239,550

4.5 BONE CONDUCTION HEARING DEVICE

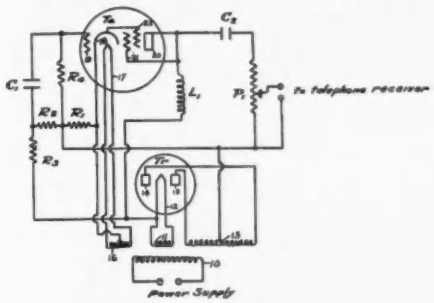
Joseph R. Cubert, assignor to Aurex Corporation.
April 22, 1941, U.S.P.O. Cl. 179–107, 8 Claims.

A piezoelectric bone construction hearing device having an electrical current input and a mechanical vibration output.

2,235,733

4.5 AUDITORY MASKING METHOD

Edward G. Witting.
March 18, 1941, U.S.P.O. Cl. 128 2.1, 3 Claims.

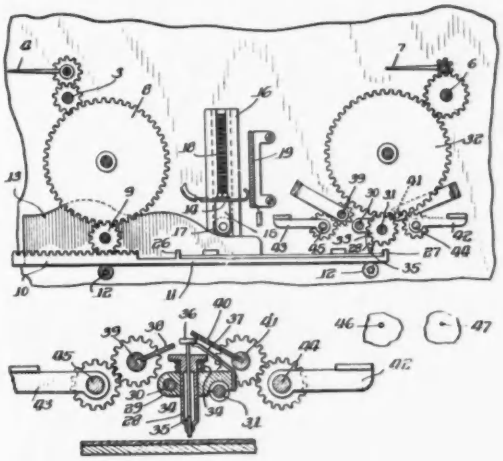


This is a method of testing hearing by generating electrical oscillations of nearly constant amplitude having fundamental frequency of approximately 120 cycles per second in addition to harmonics of said frequency, converting the electrical oscillations into audible sound, masking one ear of a patient by applying this sound thereto with an intensity sufficient to mask that ear and applying a separate sound to the other ear.

Re. 21,735

5.5 AUDIOMETER

Walter H. Huth and Joseph R. Cubert, assignors to Aurex Corporation.
March 4, 1941, U.S.P.O. Cl. 179–1, 34 Claims.

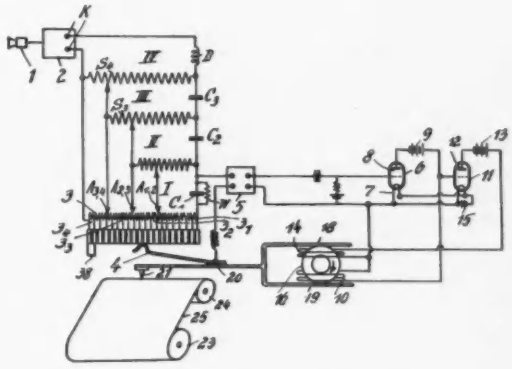


A device for testing the hearing, comprising a frequency-controlled dial, a decibel dial, a record card feeding device, coupled to and operated by frequency-controlled dial and means for making the record on the card.

2,234,573

5.15 SOUND INTENSITY RECORDER

Georg Neumann, Berlin, Germany.
March 11, 1941, U.S.P.O. Cl. 179–1, 1 Claim.

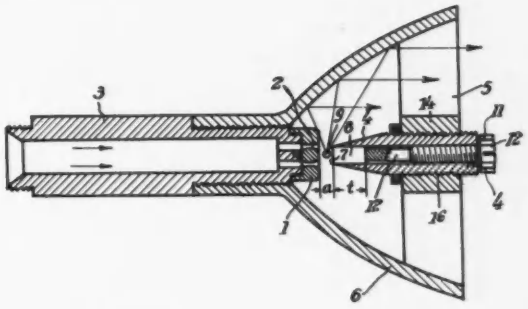


An apparatus for recording the subjective values of sound intensities.

2,238,668

5.16 DEVICE FOR THE PRODUCTION OF SOUND VIBRATIONS OF DEFINITE FREQUENCY BY MEANS OF A PIPE OR WHISTLE

Robert Wellenstein, Bremen, Germany.
April 15, 1941, U.S.P.O. Cl. 116–137, 11 Claims.

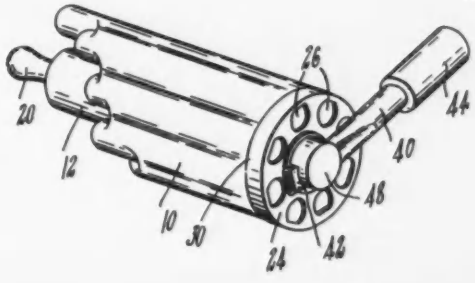


A device comprising in combination: a whistle for setting a gaseous medium in vibration to produce sound waves, a movable means for varying the frequency of the sound waves, and a temperature responsive control to maintain a predetermined sound wave frequency.

2,234,482

6.3 MUSICAL INSTRUMENT

Forest A. Stainbrook.
March 11, 1941, U.S.P.O. Cl. 84–330, 6 Claims.



2,233,948

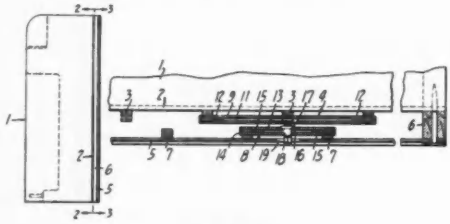
6.5, 6.9 ELECTRICAL ORGAN

Winston E. Kock, assignor to The Baldwin Company.
March 4, 1941, U.S.P.O. Cl. 84–1.21, 42 Claims.

2,237,695

6.6 SOUNDING BOARD FOR PIANOS

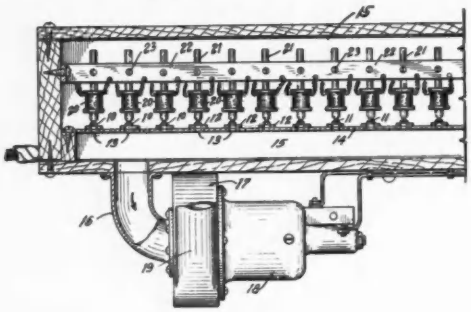
Homer W. Bell.
April 8, 1941, U.S.P.O. Cl. 84–192, 1 Claim.



2,234,490

6.9 ELECTRIC MUSIC INSTRUMENT

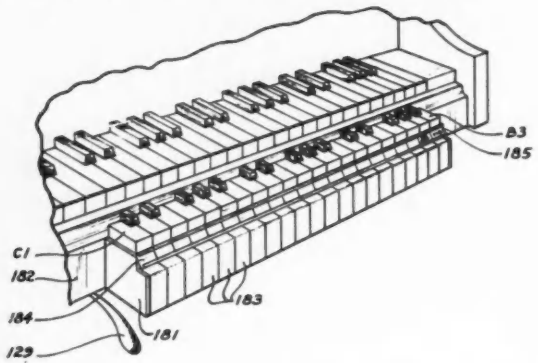
Reuben S. Gilbert, assignor of fifty percent to H. W. Michalke, and fifty percent to Gretchen Anderson Michalke.
March 11, 1941, U.S.P.O. Cl. 84–1.15, 1 Claim.



2,233,258

6.9 ELECTRICAL MUSICAL INSTRUMENT

Laurens Hammond and John M. Hanert, latter assignor to Hammond Instrument Co.
February 25, 1941, U.S.P.O. Cl. 84–1.25, 23 Claims.

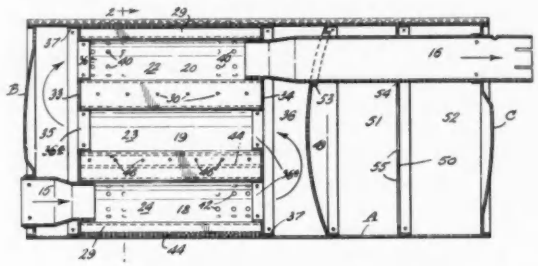


Solovox

2,235,705

7.7 MUFFLER

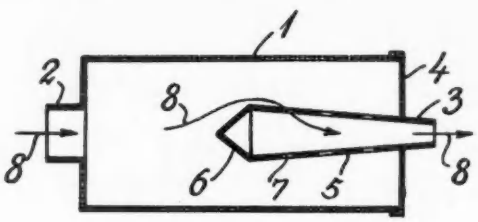
Lucien L. Haas and Gail C. Starkweather, assignors to MacKenzie Muffler Co., Inc.
March 18, 1941, U.S.P.O. Cl. 181–54, 13 Claims.



2,234,612

7.7 SILENCER FOR INTERNAL COMBUSTION ENGINES

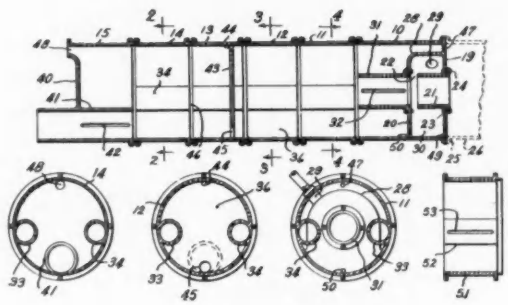
Wilhelm Peterson Wold, Oslo, Norway, assignor to Wilhelm Peterson Wold and Adolf Eger, both of Oslo, Norway.
March 11, 1941, U.S.P.O. Cl. 181–55, 6 Claims.



2,238,816

7.7 SILENCER

Hiram Hamilton Maxim and Leslie E. Knapp, assignors to The Maxim Silencer Company.
April 15, 1941, U.S.P.O. Cl. 181–48, 13 Claims.



2,233,327

7.7 SUCTION MUFFLER

Urban Sauer, assignor of two-fifths to Harry R. Levy.
February 25, 1941, U.S.P.O. Cl. 181–43, 17 Claims.

2,240,052

7.7 DEVICE FOR DESTROYING SOUND WAVES MORE ESPECIALLY UTILIZABLE AS A SILENCER FOR COMBUSTION AND EXPLOSION ENGINES

Robert Pierre Pomies, Paris, France.
April 29, 1941, U.S.P.O. Cl. 181–53, 9 Claims.

2,233,341

7.7 MUFFLER CONSTRUCTION

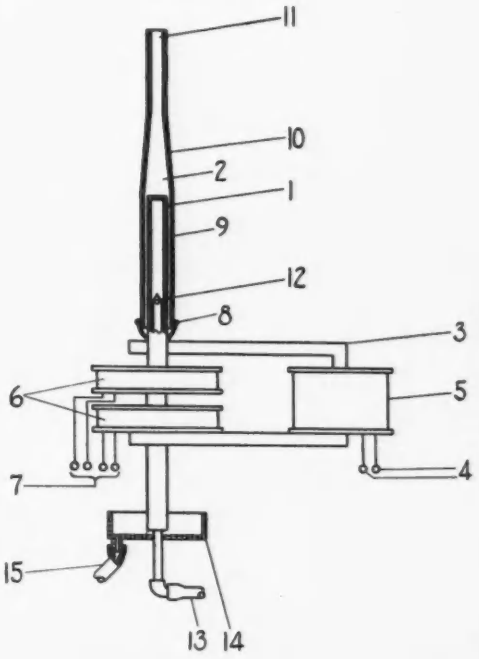
Beecher B. Cary, assignor to Hayes Industries, Inc.
February 25, 1941, U.S.P.O. Cl. 181–48, 5 Claims.

2,230,997

10.5, 10.9 METHOD OF EXTRACTING CONSTITUENTS OF LIVING CELLS

Leslie A. Chambers and Earl W. Flosdorf, assignors to University of Pennsylvania.
February 11, 1941, U.S.P.O. Cl. 167–78, 10 Claims.

This invention relates to the extraction of useful living cells, especially biologically active substances. The method involved in this patent comprises suspending a quantity of the living cells in a saline solution, subjecting the suspension to the action of intense compressional wave vibration at sonic frequency at a cavitational amplitude for a period of time not substantially greater than one hour and at a temperature not greater than 15° centigrade. This invention provides a new method involving the use of compressional wave energy and can be used only on certain desired substances which are not destroyed by treatment with such compressional wave energy.



Program of the Twenty-Fifth Meeting of the Acoustical Society of America

Sagamore Hotel, Rochester, New York

Monday Morning, May 5, at 9:30 o'clock, Senate Room

1. Corrections on the Measurements of the Velocity of Sound in Gases. W. H. Pielemeier and H. C. Hardy, *The Pennsylvania State College.* (*20 min.*)—Many of the discrepancies that have been reported on the velocity of sound in gases are a result of not making the proper corrections to standard conditions. A rigorous derivation of the velocity equation gives

$$V=\left[\frac{RT}{M}\left(f+\frac{gR}{hC_v^{\infty}}\right)\right]^{\frac{1}{2}},$$

where R, T and M have the usual meaning and C_v^{∞} is the specific heat at constant volume and infinite dilution. The quantities f, g and h are dimensionless and differ slightly from unity. They are functions of both temperature and pressure and are a measure of the imperfection of the gas. As an example of the application of the above equation, a discussion of the discrepancies of the measurements in air will be given. A list of the corrections and their magnitudes will show that neglect of many of these has caused considerable error in reported findings. Corrections on the reported values of V_0 for air give a weighted mean of $331.47\pm.06$ meters-sec.$^{-1}$, while a calculation of the value from spectrographic data, the Beattie-Bridgman equation of state, and the latest values of the fundamental constants gives $331.45\pm.05$ meters-sec.$^{-1}$.

2. Tracing Distortion in the Reproduction of Constant Amplitude Recordings. Ludwig W. Sepmeyer, *University of California at Los Angeles.* (*20 min.*)—An analysis is made of the third harmonic tracing distortion generated in the reproduction of constant amplitude recordings. Curves are shown which give, for an assumed spectral energy distribution of speech and music, the peak distortion for constant amplitude recording and for the newly adopted commercial transcription characteristics. In some cases this distortion may be as high as 5 percent at 3000 cycles and 23 percent at 8000 cycles. Comparison is made with the tracing distortion arising in the reproduction of constant velocity recordings. The problem of reducing the tracing distortion to acceptable limits is considered. Experimental verification of the theoretical predictions and the effect of record unevenness upon the tracing distortion are discussed.

3. Lip Vibrations in a Cornet Mouthpiece. Daniel W. Martin, *University of Illinois.* (*Introduced by R. H. Bolt.*) (*20 min.*)—High speed photographs of a cornet player's lips were made in rapid succession to obtain a record of the separation of the lips as a function of time, and of the shape and size of the orifice at different fundamental frequencies. Pictures were taken not only along the axis of the mouthpiece, but at right angles to it, to permit observation of the extent of lip vibration along the axis. A mouthpiece is used which is specially constructed with a Lucite rim and window. Lip separations of as much as 2.8 mm at low frequencies and axial amplitudes of 1 mm are observed. The phase at which maximum separation occurs, taking zero phase at the point of zero separation, is seen to shift in going from the lowest to the highest notes played. Fourier analyses of the separation-time curves are made by the Runge method, to obtain amplitude values for the first five harmonic components. The area of the opening is obtained as a function of the lip separation, enabling one to plot area-time curves.

4. Theatrical Uses of the Remade Voice, Subsonics and Reverberation Control. Harold Burris-Meyer, *Stevens Institute of Technology.* (*20 min.*)—In testing the remade voice, subsonics and reverberation control in legitimate theatrical production, the following requirements have been established: (1) Only such apparatus and operation techniques have been employed as fit the physical limitations of standard theaters, and which can be easily handled according to standard production practice. (2) Only such phenomena have been tested as have seemed to be demanded by existing scripts of recognized merit. Arrangement of apparatus,[1] operation technique and critical appraisal of results of tests conducted in the Stevens Theater will be discussed.

[1] J. Acous. Soc. Am. **12**, 122 (1940).

5. Industrial Noises and Industrial Deafness. W. A. Rosenblith, *University of California at Los Angeles.* (*Introduced by V. O. Knudsen.*) (*20 min.*)—During the years 1938 and 1939 a survey was conducted in France—on the behalf of Professor André Salmont—in order to determine the relationship between the intensity and the frequency distribution of industrial noises and the hearing loss which is commonly encountered in noisy professions such as boilermaking, etc. It was possible to show that there was some proportionality between the average noise level and the temporary as well as the permanent hearing loss for corresponding groups of workers. However, all attempts to relate the frequency spectrum of industrial noises to the corresponding hearing loss have failed so far, as the most important components of such noises are practically always below 1500 cycles while the hearing loss becomes severe for higher frequencies only. Thus for boilermakers having more than 15 years of employment the average hearing loss was found to be: 12.5 db at 1000 cycles, 39 at 1500, 64.5 at 4000, 77 at 6000 and 61.5 db at 8000 cycles. Certain other investigators also have reported this "high frequency deafness" after exposure to relatively "low frequency noises." It therefore appears that further experiments under conditions where one would be able to

control the intensity and the wave form of the noise might yield interesting results pertinent to an explanation and possible prevention of industrial deafness and also to the general theory of hearing.

6. The System Concept of Electroacoustical Systems. HUGH S. KNOWLES, *Jensen Radio Mfg. Co.* (*25 min.*)—The analysis of the behavior of an electroacoustic device is often much simplified by assuming idealized boundary conditions. The more rigorous consideration of the device as part of a generalized dynamical system, however, frequently materially changes the emphasis on various design factors and may even show that the simplifications vitiate the analysis. The special case of an electroacousto-electrical transducer in which the principle of reciprocity applies and in which the acoustical link is a bounded rectangular continuum is discussed. Extension of the nomenclature and methods of analysis of the passive electrical quadrupole to this case is suggested. The simplification in instrumentation which results from the use of the electroacousto-electrical quadripole is emphasized.

7. Absolute Calibration of Microphones. GUY S. COOK AND RICHARD K. COOK, *National Bureau of Standards.* (*15 min.*)—A moving-coil transducer was used both as a microphone and as a sound source in a free field to obtain an absolute free field calibration of a condenser microphone, by application of the principle of reciprocity. The free field calibration is compared with an absolute pressure calibration of the same condenser microphone, also obtained by means of the principle of reciprocity, and is compared with a free field Rayleigh disk calibration of the condenser microphone. The alternating air flow around a Rayleigh disk placed in a resonant tube was studied by means of illuminated smoke particles in order to explain qualitatively the systematic differences between reciprocity calibrations and Rayleigh disk calibrations of the condenser microphone.

MONDAY NOON, MAY 5, AT 12:30 O'CLOCK

Informal Luncheon with Society of Motion Picture Engineers

Chairman: PRESIDENT EMERY HUSE, *Society of Motion Picture Engineers.*

Addresses by:

THE HONORABLE S. B. DICKER, *Mayor of the City of Rochester.*
PROFESSOR F. R. WATSON, *President, Acoustical Society of America.*
DOCTOR HOWARD HANSON, *Director, Eastman School of Music.*

MONDAY AFTERNOON, MAY 5, AT 2:00 O'CLOCK, SENATE ROOM

8. Phase Distortion in Electroacoustical Systems. FRANCIS M. WIENER, *Harvard University.* (*15 min.*)—In the course of an investigation of phase distortion in electroacoustical systems the phase shift *vs.* frequency characteristic of a standard miniature condenser transmitter was measured by application of the principle of reciprocity. Measurements were made in a closed cavity and in free space. In analogy to the free field response the phase of the pressure in the undisturbed sound wave was taken as reference. By application of a principle of similitude the phase shift due to diffraction and cavity resonance was determined experimentally and found to be in agreement with theory. The phase characteristics of a number of commercial microphones of representative types were investigated by comparison with the standard condenser microphone. Difficulties were encountered at wave-lengths comparable with the dimensions of the microphones due to the uncertainty of microphone position with respect to the source. Relative response curves were obtained as a supplement and general check on the experimental method. The phase characteristics of a number of electrodynamic loudspeakers are presented.

9. Production and Control of Acoustic Characteristics. S. K. WOLF, *Acoustic Consultants, Inc.* (*Demonstration.*) (*20 min.*)—In recent years there has been an increasingly active search for an electroacoustic system for producing and controlling reverberation and associated phenomena. This paper describes an electro-magnetic method of producing and controlling reverberation by the use of a magnetic tape recording system. It consists of magnetically recording a sound pattern on steel tape. The signal is picked up from the tape at frequent split-second intervals and reproduced at any desired level or characteristic. The tape is arranged for driving in an endless helical loop. An obliterating head which continuously obliterates the record is placed just before the first recording head. The phenomena of reverberation and the various methods which have been

suggested by others for synthetically controlling reverberation, such as the electro-optical, electro-mechanical, mechanical recording, and the reverberation-chamber methods, are discussed. The paper also outlines other uses for the magnetic tape system in the study of acoustic phenomena both synthetically and analytically.

10. A General Purpose Vibration Meter. H. H. SCOTT, *General Radio Co.* (*20 min.*)—The popularity and usefulness of the sound level meter have created a demand for a vibration-measuring device of similar character—easy to use, accurate, and adaptable to a wide range of applications. To provide such a general-purpose vibration-measuring device a new and unusual type of instrument has been developed. Based upon the experience gained in the manufacture of hundreds of sound level meters, a stable, high gain amplifying circuit has been developed, giving a satisfactory response at frequencies as low as 2 cycles per second. The use of an acceleration-type pick-up plus two stages of electrical integration provides the user with the choice of acceleration, velocity, or displacement characteristics, all in a single instrument. Among the many other features are a stable internal calibration system, instantaneous push-button control of the integrating circuits, a semilogarithmic meter with special damping characteristics, and a single-control dual attenuator providing a wide range of sensitivity. The factors involved in the choice of the various electrical and mechanical characteristics and some actual results obtained with the instrument will be described. (Illustrated with slides.)

11. A Demonstration of the Chromatic Stroboscope as a General Purpose Frequency Meter. O. H. SCHUCK AND R. W. YOUNG, *C. G. Conn, Ltd.* (*15 min.*)—Experience has shown that the chromatic stroboscope is very useful as a general purpose frequency measuring instrument, even though it was originally developed for musical instruments. Its inherent accuracy of 1/20 percent can be made available above its nominal 4000-cycle upper limit by the use of easily constructed frequency dividers, one of which will be shown. A demonstration will be given illustrating important advantages of this method over the other available methods in range, accuracy and speed.

12. On the Perturbation of Normal Modes of Vibration. R. H. BOLT, *University of Illinois*, A. M. CLOGSTON AND H. FESHBACH, *Massachusetts Institute of Technology.* (*20 min.*)—A recently developed boundary shape perturbation theory[1] has been applied to the calculation of acoustic normal frequencies and wave patterns in enclosures which deviate somewhat from rectangularity. The method is quite general; it is applicable to any form of irregularity if the amount of distortion is "small," provided solutions for the basic form are obtainable. Specific formulas have been derived for trapezoidal and parallelogram shapes. Calculated frequencies and wave patterns are found to agree closely with experimentally measured values reported previously.[2] An experiment has been devised to test the range of validity of the perturbation calculations for one case. A small test chamber was built with walls which could be shifted continuously in plan to give trapezoids of constant area, but having any desired degree of deformity between a rectangle AB and an isosceles triangle of base $2A$ and height B. A number of normal frequencies were traced through the whole range of shapes. For wall angle shifts up to about 15° the perturbation calculations hold very well. The perturbation method promises to yield information bearing on the problem of sound diffusion in irregular rooms.

[1] H. Feshbach and A. M. Clogston, Phys. Rev. **59**, 189 (1941).
[2] R. H. Bolt, J. Acous. Soc. Am. **11**, 184 (1939).

13. The Modulation of Sound Decay Curves. R. B. WATSON, *Harvard University.* (*15 min.*)—The irregularity of decay curves has long been noted as a difficulty in the measurement of the reverberation time of a room. It has been suggested that these irregularities may be an important factor in the evaluation of the subjective acoustic qualities of a room. The departures from an exact exponential decay arise from three causes: (1) Beats are produced by interference among the resonance frequencies of the room. (2) Multiple decay rates result from the shape of the room or the non-uniform distribution of absorption on the walls. (3) The direct waves from the source and its first images are important for large or highly absorptive rooms, and at high frequencies. To investigate these phenomena, objective measurements have been made on nine rooms of widely differing sizes and shapes. Apparatus has been designed which compensates for the exponential slope of the decay, leaving only the remaining variations to be recorded by a high speed level recorder. Experimental data are presented for the nine rooms.

14. Sound Absorption Coefficients and Acoustic Impedance. RICHARD L. BROWN AND PHILIP M. MORSE, *Massachusetts Institute of Technology.* (*20 min.*)—The relation between normal acoustic impedance and the various types of absorption coefficient has been discussed and specific formulas for the coefficients in terms of acoustic impedance have been published.[1] Contours of constant absorption coefficient plotted as a function of the real and imaginary parts of acoustic impedance plotted on a linear scale are families of circles for both the *normal coefficient*, the coefficient which in the Sabine reverberation formula usually determines the initial rate of sound decay for rectangular chambers and low frequencies, and for the familiar *free-wave absorption coefficient* for any single angle of incidence. Similar contours for the Sabine or *statistical absorption coefficient*, which determines the rate of decay for completely diffuse sound, are shown to be very nearly circular. These plots, together with measured impedance curves or the equivalent electrical circuits of a sound-absorbing structure, are useful in designing materials and mountings for optimum sound-absorbing properties. The curves give theoretical explanation of the empirical value found by Sabine[2] for the average cosine of the angle of incidence for frequencies above 500 c.p.s. Graphs of the absorption coefficients plotted as functions of magnitude of impedance for various values of impedance angle show that for angles greater than 45° the treatment of a complex

impedance as a real impedance of the same magnitude introduces an error of greater than −20 percent in computing absorption coefficients.

[1] P. M. Morse, R. H. Bolt, and R. L. Brown, J. Acous. Soc. Am. 12, 217 (1940).
[2] P. E. Sabine, J. Acous. Soc. Am. 12, 317 (1941).

15. A Re-Examination of the Noise Reduction Coefficient. J. S. PARKINSON AND W. A. JACK, *Johns-Manville Research Laboratories.* (*20 min.*)—It is the present practice to call the average of the sound absorption coefficients at 256, 512, 1024 and 2048 cycles the Noise Reduction Coefficient, in an effort to assign a single figure to an absorbing material which will be useful in judging its performance in a noise quieting problem. This is recognized as a makeshift, as no single figure can represent correctly the reduction obtained. Typical noise spectra are presented and analyzed for reductions that can be expected in each frequency band. It appears that if a single figure is to be assigned the absorption coefficient at 4096 should also be considered. This is particularly true of office quieting, which is an important field of commercial noise control. In factories where heavy machinery is operating, it appears advisable to give some weighting to 128 cycles.

TUESDAY MORNING, MAY 6, AT 9:00 O'CLOCK, SENATE ROOM

A Group of Papers On Hearing

16. A Study of Sound Conduction in the Human Ear. (A Motion Picture.) H. G. KOBRAK, *The University of Chicago.* (*15 min.*)—A demonstration of various parts of the ear during the act of sound transmission. Fresh human cadaver specimens were used. The method consists of: (1) Exposure of the ear drum, ossicular chain and cochlear windows without interference with their function. (2) Magnification of the anatomical structures. (3) Reduction of the speed of vibrations for the purpose of observation and analysis. This is accomplished by the use of sinusoidal air pressure changes of subacoustic frequencies and of slow motion pictures of acoustic frequencies. The vibrations of the ear drum, ossicles, and the round window membrane are demonstrated. Resonance phenomena on the ossicular chain. Changes of intensity and frequency of the ossicular vibrations dependent on the physical characteristics of the tone. The acoustic reflexes of the middle ear muscles are shown as observed in patients with pathological ears.

17. The Effects of Pressure in the Middle Ear Upon the Electrical Responses of the Cochlea. ERNEST GLEN WEVER, CHARLES W. BRAY AND MERLE LAWRENCE, *Princeton University.* (*15 min.*)—The effects of increased air pressure in the middle ear cavity upon the cochlear responses to sound stimuli have been studied in the cat. The general result of increased pressure is a reduction in the magnitude of the response. The effects are independent of the middle ear muscles since they occur in curarized animals. The amount of reduction in the responses varies with the amount of pressure and the frequency of the stimulus tone. The role of the eardrum and other parts of the ear in the effects will be discussed.

18. Altered Acoustical Resonance of the External Auditory Canal as a Factor in the Transient Improvement of Hearing Obtained by Fenestration Operations in Chronic Progressive Deafness. EMANUEL M. JOSEPHSON, *New York, N. Y.* (*15 min.*)—Fenestration operations for progressive deafness widen and enlarge the external auditory canal. This results in altered acoustical resonance of the canal, which plays an important role in the apparent improvement in hearing that some of the cases show for a while. This factor is sufficient to explain the alterations of hearing which have been attributed to opening the inner ear and supposedly facilitating the entry of sound. This fact can be demonstrated by reconstructing the canal in operated subjects, with plastics. Altered acoustical resonance can be obtained without any of the great dangers inherent in the operation, by the use of the familiar, old-fashioned hearing tubes. Modern acoustical amplifiers are far more efficient aids to hearing. Fenestration operations severely impair the hearing in the majority of cases. There result frequently dangerous sequellae and complications, including low grade meningitis due to extension of inflammation along the tract for travel of infection to the brain which the operation creates, blindness, persistent vertigo and loss of equilibrium, painful injury to the jaw joint that interferes with chewing and nutrition, and unsightly paralysis of the face. Even when real or apparent improvement in hearing is obtained after the operation, it is usually lost eventually as the progressive deafness advances. The future of the prevention of loss of hearing by progressive deafness lies in the direction of medical treatment directed at discovered causes, such as correction of vitamin and glandular deficiencies that has proved so successful in many cases, rather than in dangerous operations on the ear that are irrationally undertaken to correct a disease of constitutional origin of which the deafness is only one local manifestation.

19. Electrical Response of the Auditory Nerve to Different Sound Intensities Under Pathological Conditions. K. LOWY, *University of Rochester.* (*15 min.*)—The method usually applied for practical hearing tests is the determination of threshold values. More recently, the importance of sound intensities above threshold has been stressed and they have been applied in human pathology. In a series

of animal experiments an attempt was made to study the electrical response to liminal and supraliminal stimuli as recorded from the auditory nerve under normal conditions and after artificial interference with the conductive and perceptive mechanism of sound. The results are compared with human audiograms.

20. Synchronization in the Higher Auditory Pathways. J. D. COAKLEY, *University of Rochester.* (*15 min.*)—If frequency of neural discharge aids us in discriminating pitches, it is reasonable to expect this frequency to appear in the subcortical centers. Examination of the potentials in the thalamus of the cat indicates that synchronization is present at this level. It has also been observed in the radiation fibers which pass into the cerebrum. Accordingly it may be concluded that synchronization persists throughout the subcortical part of the acoustic system. No definite upper frequency limit for synchronization has been found. In nearly all preparations it is possible to observe the impulses as far as 2000 to 3000 cycles; in some animals they can be observed as high as 4000 cycles. This is approximately the range in which similar observations have been made in the eighth nerve. Throughout this range the frequency of the nerve impulses is precisely the same as that of the stimulus. Since synchronization is observable throughout the subcortical part of the acoustic system—from cochlea to cerebrum—it seems likely that this is one of the means by which we distinguish one tone from another. Our results indicate, however, that synchronization is not the only possible determinant of pitch, for fiber specificity can also be observed.

21. Evidences for a Neural Quantum in Auditory Discrimination. S. S. STEVENS AND C. T. MORGAN, *Harvard University,* AND J. VOLKMANN, *Columbia University.* (*15 min.*)—A quantal theory of the neural processes mediating auditory discrimination has been formulated and subjected to experimental test. The substance of the quantal theory is this: (1) a given tonal stimulus produces an all-or-none excitation of some number of neural units (quanta) and there is left a small surplus of stimulation subliminal to the excitation of one additional unit; (2) the number of units excited, as well as the amount of subliminal stimulation of the additional unit, fluctuates randomly during the presentation of a constant stimulus. Under experimental conditions in which human observers are required to react to an abrupt increment in the frequency (or the intensity) of a pure tone, the quantal theory predicts (1) a rectilinear relation between the size of the increment and the relative frequency with which it will be detected, and (2) that the slope of this rectilinear function will be such that the increment perceived 100 percent of the time is twice the largest increment which is never detected. Experiments with increments of intensity and of frequency gave results conforming to these predictions. Data from these experiments provide a precise measure of the size of the neural quantum. This was found to vary with individuals and to be related to the intensity of the stimulus.

22. Pitch and the Missing Fundamental. DON LEWIS, *State University of Iowa.* (*15 min.*)—Jeffress[1] recently reported a study of the pitch of organ-pipe tones from which the fundamental component had been eliminated. His results, contrary to those of Fletcher,[2] indicate that the average observer does not judge pitch to remain unchanged when the fundamental is eliminated. We have been making a further study of the problem as a part of a general investigation of subjective tones. Complex stimulus tones, produced with an electrostatic type multi-harmonic generator, have typically consisted of harmonics 2, 3 and 4 in combination, with values of Δf as follows: 268, 402 and 536 cycles. Intensity levels of 50, 70 and 90 db have been employed. Eight observers, seven of whom have had advanced musical training, were instructed to adjust the frequency of an oscillator tone until its pitch was judged to be the same as the pitch of the complex tone. On the whole, the results indicate that Fletcher was probably somewhat too optimistic in his original report. Far more often than not, the adjusted frequencies were around the frequency of harmonic 2 rather than the frequency of the missing fundamental. There were important individual differences—a fact which may indicate that the amount of distortion is greater in some ears than in others.

[1] Jeffress, Am. J. Psychol. **53**, 240–250 (1940).
[2] H. Fletcher, *Speech and Hearing*, Part 4, Chap. 2; J. Acous. Soc. Am. **6**, 59–69 (1934).

23. Experiments on Short Tones. H. D. BOUMAN, *University of Rochester.* (*15 min.*)—When the duration of a tone is shortened below a certain limit, there appears a sudden change in the character of the sound. Tones of shorter duration have a more click-like character. This limit is about 8 cycles for the medium frequency range. However, the clicks are still accompanied by a pitch sensation. Bürck, Kokowski and Lichte have explained similar results as due to the relative intensities of sine wave and transients. However, if the eight-cycle group is split into two four-cycle groups, the results remain the same even though there are twice as many transients as before, which proves their explanation to be wrong. The phenomenon is entirely comparable to nervous summation, the summation time is 0.1 sec. Further evidence of the importance of nervous phenomena is obtained when the frequencies of the groups differ. The result is a gliding tone, a perfect analogy of apparent movement in the visual field. Other evidence of nervous phenomena in hearing is obtained from strength-duration curves. They are typical of those obtained in nerves and are identical for different frequencies. The pitch difference-limen below the liminal duration is 40 cycles. This means that gross determination of frequency being a peripheral process, there is nevertheless evidence of a central process for the fine determination of pitch. Other evidence of neural phenomena is found in experiments on masking where a definite summation time can be established. Hartridge's experiments on phase reversal can be readily explained as being of nervous origin.

TUESDAY AFTERNOON, MAY 6, AT 2:30 O'CLOCK

UNIVERSITY OF ROCHESTER—MOREY HALL—RIVER CAMPUS

A.—Round Table Discussion on Distortion in the Ear

Chairman, DON LEWIS, *State University of Iowa*

Participants: H. D. BOUMAN, *University of Rochester*
C. W. BRAY, *Princeton University*
HALLOWELL DAVIS, *Harvard Medical School*
F. A. FIRESTONE, *University of Michigan*
HARVEY FLETCHER, *Bell Telephone Laboratories*
W. A. MUNSON, *Bell Telephone Laboratories*
E. PETERSON, *Bell Telephone Laboratories*
JOHN C. STEINBERG, *Bell Telephone Laboratories*
S. S. STEVENS, *Harvard University*

B.—Demonstration of Animal Experiments

E. A. CULLER, *University of Rochester*

1. Measuring the threshold of hearing in a trained cat.
2. Measuring the ability of a trained animal to discriminate frequencies which are well above threshold.
3. Demonstrating the cochlear and cortical response to the same tone in an acute preparation.
4. Demonstrating the effect of partial section of the eighth nerve, by electrical procedure.

WEDNESDAY MORNING, MAY 7, AT 9:30 O'CLOCK, EASTMAN THEATER

Joint Meeting of the Society of Motion Picture Engineers and the Acoustical Society of America

Symposium on the Stereophonic Sound-Film System by the Bell Telephone Laboratories, New York, N. Y.

24. General Theory. HARVEY FLETCHER.—The general requirements are discussed for an ideal recording-reproducing system as determined by the characteristics of hearing of a typical group of persons listening in a typical concert hall or theater. Quantitative values are set down as ideal objectives. Although microphones, loudspeakers and amplifiers which had been developed for the stereophonic transmission system were available for meeting these objectives, no recording medium was known which would record the wide dynamic range of intensity levels which the objectives indicated was necessary. However, this wide intensity range objective was met by using a compandor in the electrical system. A general discussion is given of the reasons for choosing the particular compandor used, for using variable area rather than variable density on the recorded film, for using three instead of a greater or lesser number of channels. A general description of the stereophonic sound film system is given, including the enhancement feature. This feature makes it possible to re-record from the original recording, at the same time making any desirable changes in the dynamic range or frequency response in each of the three channels.

25. Mechanical and Optical Equipment. E. C. WENTE, R. BIDDULPH, L. A. ELMER, AND A. B. ANDERSON.—The same mechanism is employed for propelling the film in both recording and reproducing. To permit recording of the longer orchestral selections without interruption, the machines are designed to handle film in 2000-foot lengths. Special features of the film-propulsion system for obtaining great uniformity of speed at the translation points are described. The three signal- and one control-channel currents are recorded by means of light valves of identical construction. All four tracks are exposed while the film is passing over a free-running supporting roller, mounted on the same shaft with a new type of internally damped roller. In reproduction, each track is exposed through an objective of high aperture to light from an incandescent source. After passing through the film, the light from each track is carried by a glass rod to a photoelectric cell.

26. Pre- and Post-Equalization of Compandor Systems. J. C. STEINBERG. *Technical Demonstration.*—In order best to fit the volume range of the program material into the volume range available in sound film, it is generally advantageous to pre-equalize the program material before recording, and to compensate for the equalization by means of a complementary post-equalizer on reproduction. The type and amount of pre-equalization depend upon the properties of hearing and on the characteristics of the program material and the film noise. This paper discusses the relations between these quantities for systems using compandors, where the film noise varies up and down in level as the compandor gains vary. Ideally, different types of pre-equalization are needed for different types of program material, and a compromise must be made if a single type is to be used. The considerations leading to the choice of the pre-equalization used in the stereophonic recording and reproducing system are discussed.

27. Electrical Equipment for the Stereophonic Sound-Film System. W. B. SNOW AND A. R. SOFFEL.—An electrical system is described which permits the use of sound film, with its limited signal-to-noise ratio, as a recording medium for wide-range stereophonic reproduction of symphonic music. Noise reduction is accomplished both by pre-equalization, rising to 18 db above 8000 cycles, and by automatic signal compression and expansion of 30 db. To secure maximum suppression of noise and freedom from distortion, a pilot-operated, flat-top compandor system was selected. In each channel low level signals are recorded on a separate track with constant gain 30 db above normal, which places them above the film noise. Higher-level signals cause automatic gain reductions and are recorded at substantially full modulation. These signals vary the intensity of a pilot tone, which in turn controls the compressor gain. There is a pilot frequency for each of the three channels, and the three are combined and recorded together on the fourth film track. During reproduction they are separated by filters, and operate expandors which restore the signals to their original forms but reduce the noise to inaudible levels. The compressor and expandor gains are made proportional to pilot level in db, and the expandor range over which this relation holds is 45 db. Therefore a 15-db variation in average pilot level during reproduction causes a corresponding average level change but no distortion. This is used to allow expansion of the original signal intensity range during recording or re-recording by simple gain controls in the pilot circuits. The paper describes the apparatus and circuits developed to accomplish these results, and discusses the frequency, load, distortion, noise, and dynamic characteristics of both constant and variable gain elements. Also included are considerations of microphone and loudspeaker arrangement and equalization to secure high fidelity of reproduction.

WEDNESDAY AFTERNOON, MAY 7, AT 2:00 O'CLOCK, GLASS HOUSE, HOTEL ROOF

Joint Meeting of the Society of Motion Picture Engineers and the Acoustical Society of America

28. A Light Valve for the Stereophonic Sound-Film System. E. C. WENTE AND R. BIDDULPH.—This paper describes a light valve incorporating large electro-magnetic damping and operating directly through the ribbon resonance region. Resonance response is only 5 db above low frequency response and so permits easy equalization. A suitable equalizer provides uniform string displacement per unit driving voltage over the band 30–14,000 cycles with very nearly constant phase shift per cycle. Problems of structure and size have furnished a mechanical design having several interesting features, among which are mechanical robustness, protection against dirt and moisture, built-in ribbon and optical adjustments, and an optical system integral with the valve structure thus permitting rapid replacement of valves in the recording machine. This unit has proved a rugged, stable, light modulator especially free from intermodulation products.

29. Internally Damped Rollers. E. C. WENTE AND A. H. MÜLLER.—Special damping rollers, capable of damping oscillations of rotating shafts without adding a steady load, were first devised by Prof. H. A. Rowland. These rollers had either an annular channel along the periphery filled with a liquid, or a wheel mounted loosely on a shaft coaxially fixed in an outer shell, the interspace being filled with a liquid. The theory of the action of such rollers in reducing fluctuations in the speed of rotation caused by disturbances from either the load or the driving side is developed and the results are illustrated by graphs. A new form of roller is described in which liquid filling an annular channel within the shell of the roller is coupled to the shell by a mechanical resistance.

30. A Non-Cinching Film-Rewind Machine. L. A. ELMER.—Cinching, or the sliding between layers of film within a reel, produces scratches and surface abrasions which increase the film noise level. Cinching is more apt to occur in rewinding than anywhere else in the normal usage of sound film. At the beginning of rewinding, when the supply reel is full and the take-up reel is empty, a small amount of torque is needed for rotating the take-up reel. Under this condition the film will be wound rather loosely. When the supply reel is nearly empty, relatively high film tension is required to produce a given torque on the supply reel. The torque to be applied to the take-up reel will then be high, on account of both the high film tension and the large radius arm of the film spiral on the

reel. This high torque is almost certain to cause cinching in the loosely wound bottom portion of the reel. The conditions to be satisfied if cinching is to be avoided are analyzed. A power-driven rewind is described which meets these requirements. The film tension is controlled by the weight of the film on the supply reel at all times during the rewind.

31. Progress in Three-Dimensional Photography. J. A. NORLING, *Loucks and Norling, New York, New York* (*Demonstration*).

32. Solar Prominences in Motion. R. R. MCMATH, *McMath-Hulbert Observatory, Lake Angelus, Pontiac, Michigan* (*Demonstration*).

WEDNESDAY EVENING, MAY 7, AT 8:15 O'CLOCK, EASTMAN THEATER

Joint Meeting of the Society of Motion Picture Engineers and the Acoustical Society of America

Demonstration of Stereophonic Sound-Film System by the Bell Telephone Laboratories

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SUPPLEMENTARY PROGRAM

33. A Problem in Acoustically Treated Enclosures. G. L. BONVALLET, *Burgess Battery Company, Acoustic Division, Chicago.*—The low frequency energy prevalent in sound treated rooms becomes perceptible and even objectionable as the size of the room decreases. The doorless acoustically treated telephone booth is subject to this difficulty in a few installations of prevailing high intensity low frequency energy. Increasing the mass or stiffness of the components of the structure decreases the resonant frequency. These solutions, however, lead to a product of prohibitive cost. Mismatching and damping of the panels lead to another solution. Efforts have been made along these lines to produce a marketable structure. Experimental models have been made which are a step in the right direction, but the "natural" has not yet been found. These models have by no means exhausted the ingenuity of combining materials to obtain the desired effect.

34. Localization of Response in the Cochlea as Determined by Electrical Recording. E. H. KEMP AND PARKER JOHNSON, *Duke University.*—Electrical responses from the cochlea of the guinea pig were studied by means of an amplifier, a cathode-ray oscillograph and a wave-analyzer. The guinea pig was anesthetized with dial and urethane, put under artificial respiration and placed in a "soundproof" room. A beat-frequency oscillator, attenuator and speaker provided tones which were delivered to the ear of the guinea pig through a rubber tube and a speculum which had been sewed into the external meatus. The cochlear response to frequencies of 100, 200, 400, 600, 1000, 2000, 4000, and 6000 cycles per second was recorded from selected positions on each turn of the cochlea. For each frequency a series of intensities was used and a log response–log relative sound intensity curve obtained. From these curves the relative intensity of sound on each frequency necessary to elicit a response of three microvolts was determined for each recording position. The data obtained make it possible to construct a map of the cochlea which meets the requirements of the place theory of audition, and which confirms a map of the cochlea previously constructed by Culler from data obtained by a somewhat different method.

35. Contribution Offered Towards a Discussion of the Paper "Pitch and the Missing Fundamental."* WILLIAM BRAID WHITE, *The School of Pianoforte Technology, Chicago.*—For several years we have used in this laboratory a set of steel bars, each mounted on a resonating box and respectively tuned to the frequencies 110, 220, 330, 440, 550, 660, 770, 880 and so on in the Fourier series, to and including 1760 c.p.s. This gives in effect a fundamental tone with the succeeding Fourier harmonics up to the 16th inclusive. By repeated experiment with many students taking courses in the theory and practice of tuning pianos in equal temperament, during the last three years, we have found that, if we sound several of the bars simultaneously, choosing the members of the series in their regular succession, that is to say, such a series as 220, 330, 440, 550, 660, we always hear clearly and, as it were, beneath the simultaneous sounds, blended together into a chord, the fundamental tone 110. When again we take such a series as 440, 660, 880, 1100, we hear the fundamental 220. When we take 660, 990, 1320, 1560, we hear the fundamental 330. When again we have taken an irregular series, such as 330, 550, 660, 880 and 990, we have always heard a tone of pitch corresponding with the frequency of the smallest number of beats between any pair of the bars, namely 110. In the case above mentioned, the 110 is very distinct, with 220 existing simultaneously, and traces of 330 also. The most important fact however seems to be that the lowest frequency deducible, namely 110, is always, in the cases mentioned, definitely and distinctly heard. It should be understood that these bars are excited simply by blows delivered with felt-covered hammers, and that the beat-tones, as I shall call them, are therefore feebler than they would be if the bars were excited electrically at relatively large amplitudes, and were steadily sustained thereat. Phenomena such as these described have been explained by the Koenig theory of beat-tones, which states that when the number of beats between two frequency-generating

units exceeds the minimum number of atmospheric pulses sufficing to arouse a sensation of sound (that is to say, when the number exceeds 16 or thereabouts), sensations of tone are aroused and identified, giving sensations of pitch corresponding to the beat-frequencies. Presumably such sensations may be described as having subjective origin, although it appears that the psycho-physiological foundation of any such theory has hardly yet been laid firmly. What seems more important for the moment is that our experiences corroborate the observations made, and conclusions reached, by Fletcher, as shown in his paper.[1] We do not overlook the fact of Fletcher's experiments pointing to the fundamental tones being regarded as the actual pitch-sensation generators for the groups of simultaneous harmonic sounds used by him, while in our case we recognize the fundamental tones as forming weak but very distinct roots to the chords which are constituted by the simultaneous harmonic tones. The distinction however does not appear to be essential.

* Abstract No. 22 in this issue.
[1] H. Fletcher, J. Acous. Soc. Am. **6**, 67 (1934).

POSTSCRIPT.—For the purpose of obtaining an additional check on the findings above set forth, the tone-bars mentioned there have been once more sounded in the same way, and the sound waves have been picked up by a model K2 Astatic microphone and thus put into the system of a Conn Chromatic Stroboscope, in order to discover whether the beat-tones or fundamentals of the various series would or would not give a visible sign of their existence on the rotating disks of the instrument.

The following were the tests and the results:

Tone-bars 330 and 440 sounded simultaneously. Stroboscope showed faint but definite image on the 110 band of the *A* disk.

Tone-bars 440 and 550 sounded simultaneously. Same result.

Tone-bars 330, 440 and 550 sounded simultaneously. Stroboscope showed definite 110 image and fainter but visible 220 image.

The 110 image lasted longer and was strong throughout the life of its generating beat-tone.

Tone-bars 220, 330, 440, 550, 660, 770, 880, 990 and 1100 corresponding to the 2nd, 3rd, 4th, 5th, 6th, 7th, 8th, 9th and 10th harmonics of 110 were sounded simultaneously. The 110 image corresponding to a beat-tone equal to the fundamental frequency 110 was plainly visible.

Tone-bars 660 and 990 sounded simultaneously, and tone-bars 660, 990 and 1320 sounded simultaneously. Both showed very clear 330 image on the *E* disk.

Each result was accepted only after at least three determinations, and one or two were repeated six times. Three persons took part in the experiment, Messrs. Wallace Beecher and Hugh Wolford, students of this School, and the writer of this note. It appears that the microphone received physical impressions corresponding to the sound waves set up by ordinary tone generators giving 110, 220 and 330 c.p.s respectively. This result *supports* the theory of beat-tones having an existence independent of any occurrence within the inner ear. No more than this is suggested.

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